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EVALUATION OF LARGE Ti-6Al-4V AND IMI 679 FORGINGS

R. F. Simenz
W. L. Macoritto

Lockheed-California Company

TECHNICAL REPORT AFML-TR-66-57

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FOREWORD

This report was prepared by the Lockheed-California Company, a division of the Lockheed Aircraft Corporation, under Contract AF33(615)-2690. The contract was performed under Project No. 7381, "Materials Application", Task No. 738106, "Materials Information Development". The time period covered by this report is 1 April 1965 to 28 February 1966. The report was submitted by the authors in February 1966 for publication as an RTD Technical Report.

The work was administered under the direction of the Air Force Materials Laboratory, Research and Technology Division, by Lt. H. Lachmann, Project Engineer.

At the Lockheed-California Company, this program was conducted under the direction of Mr. H. B. Sipple, Research and Development Engineer, Materials and Processes. Mr. R. F. Simenz was Project Leader, assisted by Mr. W. L. Macoritto. Technical consultation was provided by Mr. V. E. Dress and Mr. G. G. Wald. Material property testing was under the direction of Mr. R. L. Adamson, assisted by Mr. S. L. Pendleberry. Forging testing was under the direction of Mr. R. H. Wells, assisted by Mr. C. S. Oswell. Structural analysis of the F-104 fuselage ring fitting was conducted by Mr. K. P. Durham.

Wyman-Gordon Company personnel participating in the program were Mr. J. J. Zecco, Jr. and Mr. R. E. Sparks, who supervised production of the forgings and coordinated metallurgical and material property testing.

This technical report has been reviewed and is approved.

D. A. SHINN
Chief, Materials Information Branch
Materials Applications Division
AF Materials Laboratory

ABSTRACT

This report describes the evaluation of large, closed-die forgings of two titanium alloys. Four forgings each of Ti-6Al-4V and IMI 679 were used in the evaluation. Property tests that were conducted included tension, notched tension, compression, Tuckerman modulus, shear, bearing, fracture toughness and smooth and notched axial fatigue. Thermal exposure and susceptibility to delayed failure in salt water were also evaluated in each alloy. Static properties were generally slightly better in the Ti-6Al-4V alloy. However, the IMI 679 provided significantly better smooth and notched fatigue values. Both alloys had good fracture toughness at room temperature and at -110°F. Static and fatigue tests were conducted on one forging each of Ti-6Al-4V and IMI 679. The Ti-6Al-4V part gave the better static test performance. Both titanium alloys exhibited strength/weight efficiency superior to a 4340 steel part tested in a previous program. The fatigue test life of the IMI 679 part was approximately 60% better than that of the Ti-6Al-4V part; however, the Ti-6Al-4V may not have been a representative sample due to minor metallic inclusions found in the fatigue-tested part. Based on these results the IMI 679 alloy shows promise for improved performance over Ti-6Al-4V as well as over other titanium alloys in fatigue critical applications. The material property data and forging static and fatigue test results indicate that Ti-6Al-4V and IMI 679 compare favorably with two other titanium alloys, Ti-6Al-6V-2Sn and Ti-13V-11Cr-3Al, which were evaluated in a previous program.

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SYMBOLS

F_{bru}	Bearing ultimate strength
F_{bry}	Bearing yield strength at 0.2% offset
f_{max}	Highest value of gross area stress
f_{mean}	Mean gross area stress
f_{min}	Lowest value of gross area stress
f_{vary}	Maximum gross area stress minus mean gross area stress
F_{tu}	Tensile ultimate strength
^oF	Degrees Fahrenheit
ksi	Kips (1,000 pounds) per square inch
K_{1c}	Plain strain critical stress intensity factor (Fracture Toughness)
K_{1i}	Sustained load environmental stress intensity limit
K_t	Theoretical stress concentration factor
N	Number of cycles
NTS	Notched tensile strength
P	Load (lbs)
P_Y	Horizontal load (lbs)
P_Z	Vertical load (lbs)
P_{max}	Maximum load (lbs)
R	Ratio of minimum to maximum stress
R. A.	Reduction of area
RT	Room temperature
σNet	Net fracture stress
σYS or F_{ty}	Yield strength at 0.2% offset

Section I

INTRODUCTION

Substantially increased usage of titanium alloy forgings is anticipated in current and future weapon systems because of the structural advantages offered by this class of materials. The purpose of this program was to provide material property data which will form a basis for the reliable use of two heat treated titanium alloy forgings and to demonstrate the actual capabilities of state-of-the-art production forgings of these alloys in high performance aerospace structural applications.

Four forgings of the Ti-6Al-4V alloy and four forgings of the IMI 679 alloy were produced for evaluation in this program. The titanium forging configuration used is a modification of a production F-104 fuselage ring fitting normally made from 4340 steel. Two forgings of each alloy were cut up and subjected to comprehensive material property tests. One forging of each alloy was tested to failure in a full-scale fatigue test and a second forging of each alloy was tested to destruction statically.

In a previous Air Force program (Reference 1) a similar evaluation was conducted on forgings of two other titanium alloys, Ti-6Al-6V-2Sn and Ti-13V-11Cr-3Al. Data obtained in that program are compared with data obtained in this program to illustrate the relative merits of four of the leading candidate titanium forging alloys.

Participation by the Wyman-Gordon Company in the program included production of the titanium forgings, preliminary heat treatment evaluation, and a portion of the metallographic and tensile property evaluation.

Section II

SUMMARY

The purpose of this program was to conduct an evaluation of large titanium alloy forgings in order to provide a basis for their reliable use in advanced weapon systems. Four closed-die forgings were fabricated from each of two alloys, Ti-6Al-4V and IMI 679. The forging configuration was a modified F-104 aft fuselage ring fitting. Results obtained in this program were to be compared to results obtained on Ti-6Al-6V-2Sn and Ti-13V-11Cr-3Al investigated in a similar program (Reference 1).

Material properties were determined by testing specimens cut from forgings of Ti-6Al-4V and IMI 679. Properties evaluated included tension and compression at -110°F, room temperature (72°F), and 550°F; shear and bearing at room temperature and 550°F; notched tension and fracture toughness at -110°F and room temperature; and smooth and notched axial fatigue. Other test variables included specimen location and grain direction. The effect of a 1000-hour exposure at 550°F on smooth and notched tension and on fracture toughness properties was also evaluated. Billet tension properties in all three grain directions were obtained for comparison with similar properties in the forgings.

Tension and compression moduli were determined by Tuckerman optical strain measurements. Susceptibility to environmental delayed failure of pre-cracked specimens in the presence of salt water was also evaluated.

The effect of temperature on ultimate tensile strength of the four titanium alloys is shown in Figure 1. As shown in this figure, the ultimate tensile strength in Ti-13V-11Cr-3Al and IMI 679 showed the least effect of 550°F testing. The effect of temperature on yield strength is shown in Figure 2 and generally exhibits the same trend as the ultimate strengths.

Tensile properties of the Ti-6Al-4V and IMI 679 were within the expected ranges. Generally, both alloys showed only minor variations in tensile properties with grain direction or location. The IMI 679 alloy was exceptionally uniform and exhibited a minimum range in tensile properties. This is clearly evident in Figure 3 which presents the room temperature tensile strength variation from edge to center in the forging thick section for IMI 679 and Ti-6Al-4V. Similar data on Ti-6Al-6V-2Sn and Ti-13V-11Cr-3Al (Ref.1) are shown for comparison. Tensile strengths in the light sections and edge locations of the heavy section were consistently higher than at any other location in both Ti-6Al-4V and IMI 679.

Values of elongation and reduction of area were very high at all locations and test temperatures in both the Ti-6Al-4V and IMI 679 forgings. The lowest values measured at room temperature were 8% elongation and 10% reduction of area in the Ti-6Al-4V forging and 10.5% elongation and 30% reduction of area in the IMI 679 forgings. The IMI 679 had the highest ductility of the four alloys evaluated in the two programs followed, in order, by Ti-6Al-4V, Ti-6Al-6V-2Sn, and Ti-13V-11Cr-3Al.

Notched-to-unnotched tensile strength ratios of 1.35 and higher were obtained in all grain directions and test locations in Ti-6Al-4V and IMI 679 materials. Figure 4 compares notched-to-unnotched tensile strength ratios measured in the longitudinal grain direction at various forging locations for both of these alloys, as well as for Ti-6Al-6V-2Sn and Ti-13V-11Cr-3Al which were tested previously (Ref. 1).

Unstressed thermal exposure to 550°F for 1000 hours had no apparent effect on the strength or ductility of the Ti-6Al-4V and IMI 679 smooth tensile properties. The notched tensile properties also remained unaffected after exposure.

Fracture toughness was measured at room temperature and -110°F in Ti-6Al-4V and IMI 679. A pre-cracked round bar specimen was used in these tests; the results are given in Figure 5. Results obtained (Ref. 1) on Ti-6Al-6V-2Sn and Ti-13V-11Cr-3Al are also shown for comparison in this figure. It is evident that Ti-6Al-4V showed the highest fracture toughness values, followed by IMI 679 and Ti-6Al-6V-2Sn. The Ti-13V-11Cr-3Al showed the lowest fracture toughness of the four materials. Unstressed exposure at 550°F for 1000 hours did not have a significant effect on the fracture toughness of any of these alloys.

At room temperature and at -110°F, the compression properties of Ti-6Al-4V and IMI 679 were in the same range as the ultimate tensile strengths of each alloy. However, at 550°F the compression yield strengths of both alloys dropped off more rapidly than the ultimate tensile strengths. The effect of temperature on the compression yield strengths of Ti-13V-11Cr-3Al and Ti-6Al-6V-2Sn (from Ref. 1), and Ti-6Al-4V and IMI 679 are presented in Figure 6.

Room temperature ultimate shear properties of Ti-6Al-4V and IMI 679 were similar to those obtained on Ti-6Al-6V-2Sn and Ti-13V-11Cr-3Al (Ref. 1). However, at 550°F both the Ti-13V-11Cr-3Al and Ti-6Al-6V-2Sn had higher shear strengths than the Ti-6Al-4V and IMI 679.

Ti-6Al-6V-2Sn had the highest room temperature bearing strength of the four alloys. The Ti-13V-11Cr-3Al had the highest bearing strength at 550°F.

Smooth and notched axial fatigue properties in Ti-6Al-4V and IMI 679 are summarized in Figures 7 and 8. Results obtained (Ref. 1) on Ti-13V-11Cr-3Al and Ti-6Al-6V-2Sn standard and low oxygen materials are also shown in this figure for comparison. The highest smooth and notched fatigue strengths were exhibited by the IMI 679 and Ti-6Al-6V-2Sn with the IMI 679 showing a significantly higher endurance limit than any of the other alloys. As stated in Reference 1, there appears to be a definite improvement in notched fatigue properties in low oxygen content Ti-6Al-6V-2Sn when compared to standard oxygen content material.

Notched, pre-cracked bend bars were tested to determine the susceptibility of forged Ti-6Al-4V and IMI 679 to delayed failure in salt water. The data obtained from these tests indicate a relatively high resistance to delayed failure for both heavy and light sections of Ti-6Al-4V and light sections of IMI 679 material. The IMI 679 material from the heavy section center location exhibited substantial susceptibility to delayed cracking in salt water.

Precision room temperature tension and compression modulus data are presented below. All values shown were obtained in the longitudinal grain direction.

Alloy	Tension Modulus 10^6 psi	Compression Modulus 10^6 psi
Ti-13V-11Cr-3Al	15.7	16.0
Ti-6Al-6V-2Sn	15.8	16.2
Ti-6Al-4V	17.1	17.4
IMI 679	15.7	16.1

No significant difference in modulus was noted between the longitudinal and long transverse grain directions in any of the alloys.

Static tests were conducted on one forging each of Ti-6Al-4V and IMI 679. The target was to have a strength equal to the 180-ksi, 4340 steel forging design. This was accomplished by increasing critical dimensions in the titanium forgings to compensate for the differences in strengths. The dimensional increases in the lower strength Ti-6Al-4V and IMI 679 forgings were proportionately greater than those in the higher strength Ti-6Al-6V-2Sn and Ti-13V-11Cr-3Al previously tested (Ref. 1).

Static test failure initiated in the upper flange in both the Ti-6Al-4V and IMI 679 parts. The Ti-6Al-4V showed almost complete shear mode fracture, while the IMI 679 part had less than 15% shear-type fracture.

The static test results on the two parts are given in Figure 9; test results (Ref. 1) on Ti-6Al-6V-2Sn, Ti-13V-11Cr-3Al and 4340 steel are also shown for comparison. It was explained in Reference 1 that the high failure strength in the steel part was a result of its ultimate strength being 205 ksi instead of the intended 180 ksi. Figure 10 compares the static strength efficiency (expressed as failure strength divided by part weight) of all the materials.

Full-scale, spectrum-type fatigue testing was conducted on one forging each of Ti-6Al-4V and IMI 679. In Figure 11 the test results on these alloys are compared to the values previously obtained (Ref. 1) on Ti-6Al-6V-2Sn, Ti-13V-11Cr-3Al and 4340 steel. These results indicate that Ti-6Al-4V and IMI 679 were superior to the other two titanium alloys. An increase in fatigue life was expected in the Ti-6Al-4V and IMI 679 parts since these alloys had increased local section sizes which decreased local stresses during fatigue loadings. Metallurgical studies revealed iron-rich inclusions at the fatigue crack origin in the Ti-6Al-4V part which may account for the large difference in its fatigue life compared to the IMI 679 part.

The fatigue life of the IMI 679 part very nearly approximated that of the steel part which is considered outstanding since the IMI 679 part was 31% lighter and had been machined from a heavy section, whereas the steel was forged to final dimensions.

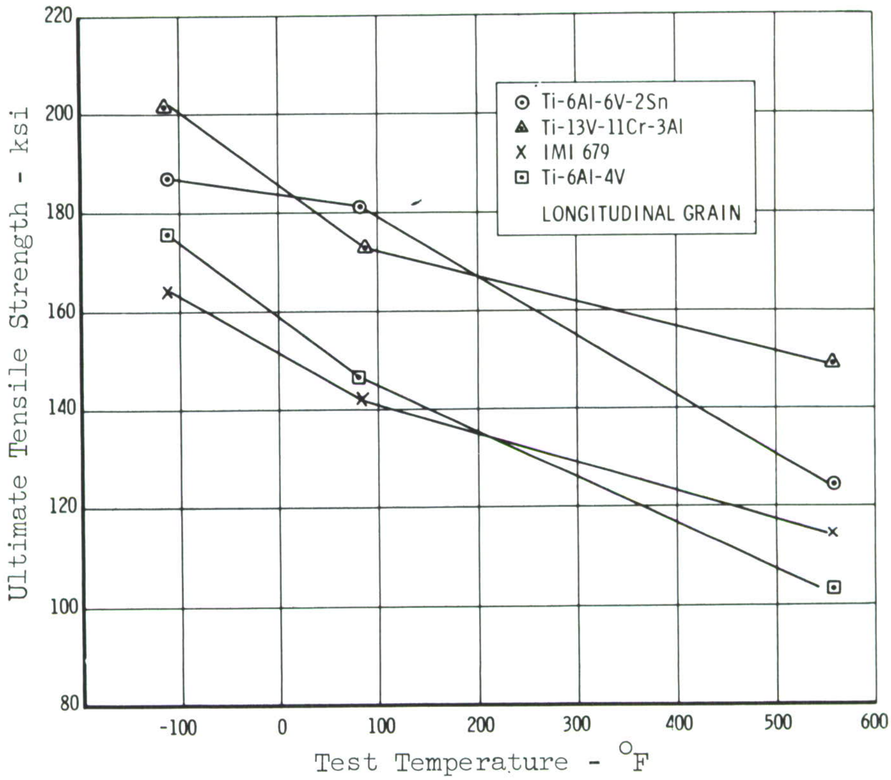


Figure 1. Effect of Temperature on Ultimate Tensile Strength

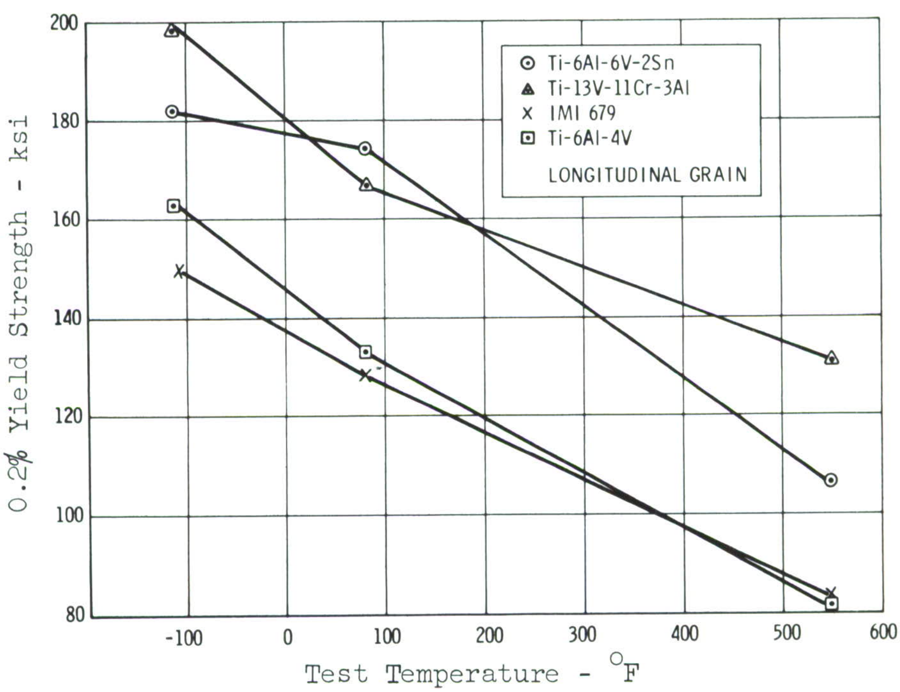


Figure 2. Effect of Temperature on Tensile Yield Strength

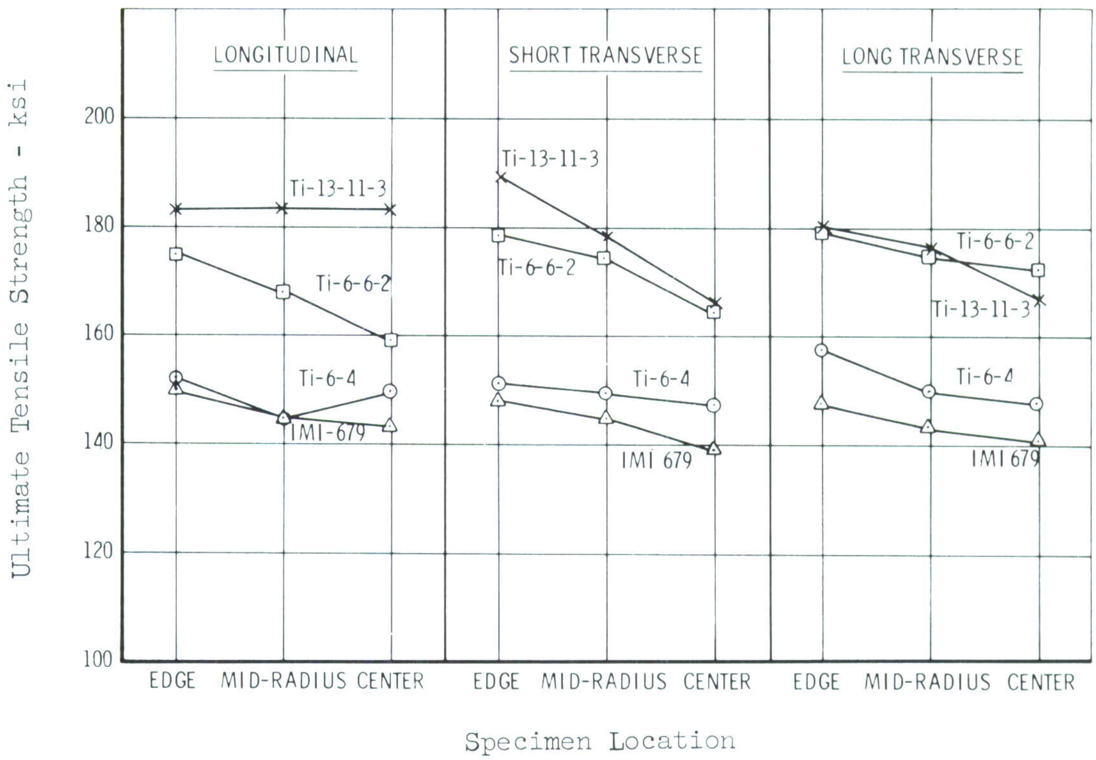


Figure 3. Variation of Thick Section Ultimate Tensile Strength with Location and Grain Direction

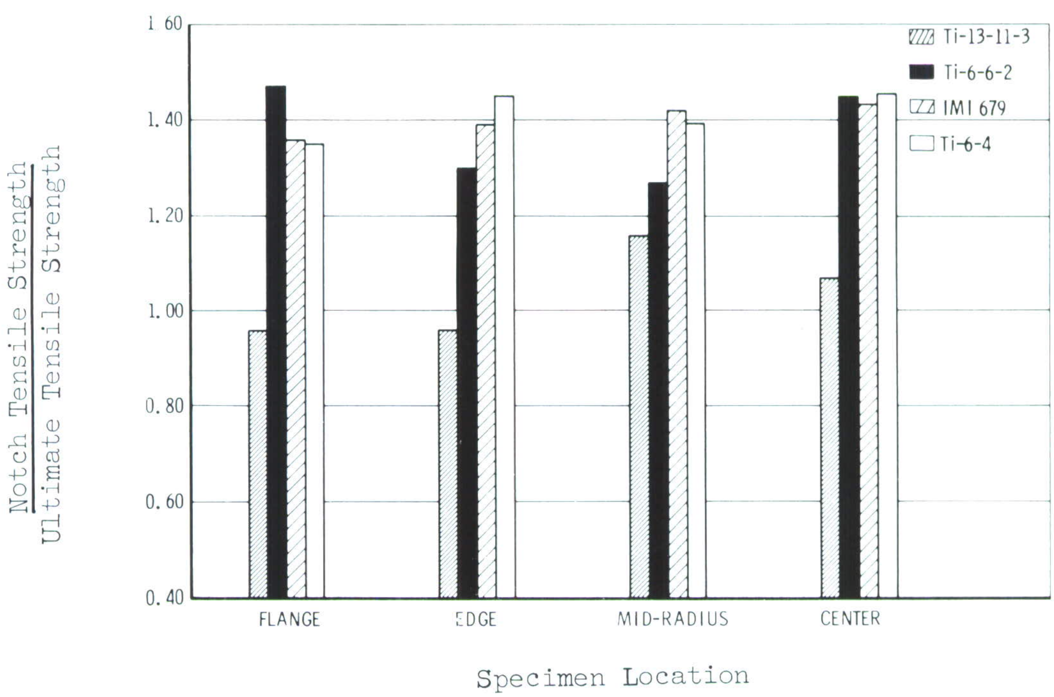


Figure 4. Room Temperature Notched Tensile Properties ($K_T = 3.9$)

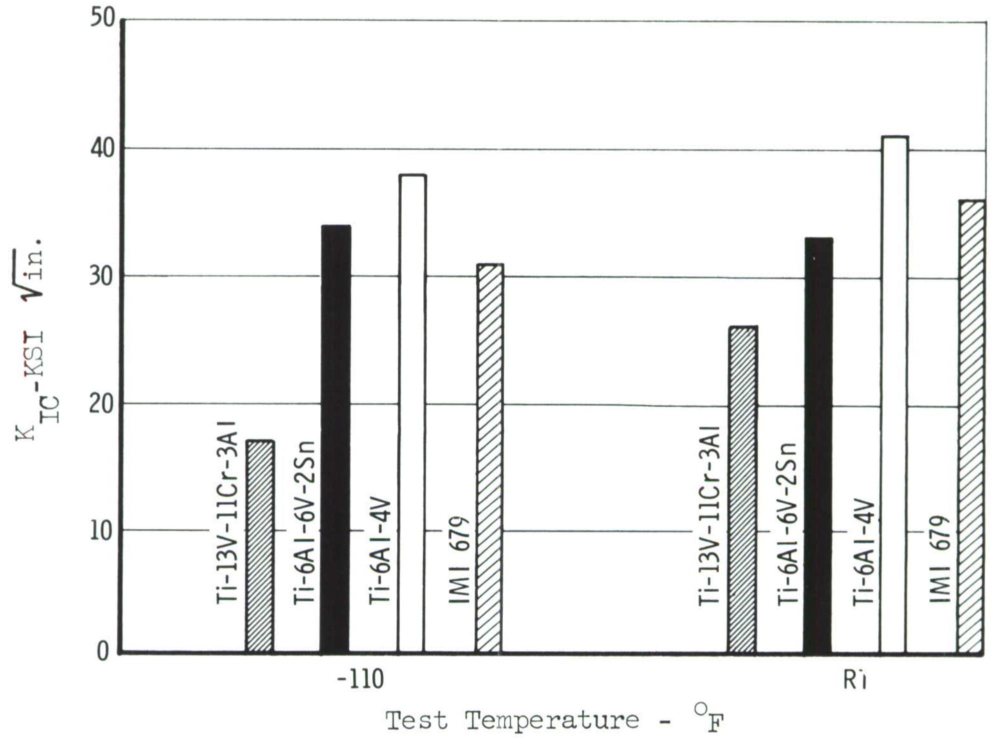


Figure 5. Comparison of Short Transverse Fracture Toughness Properties

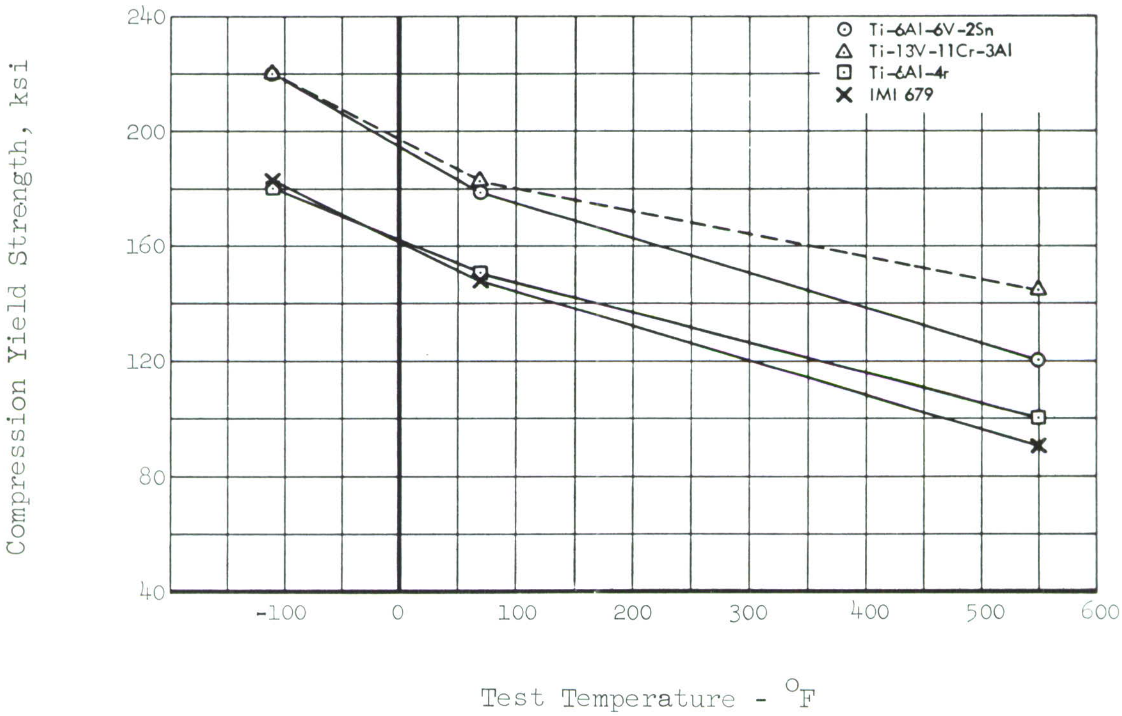


Figure 6. Effect of Temperature on Compression Yield Strength (Transverse Grain Direction)

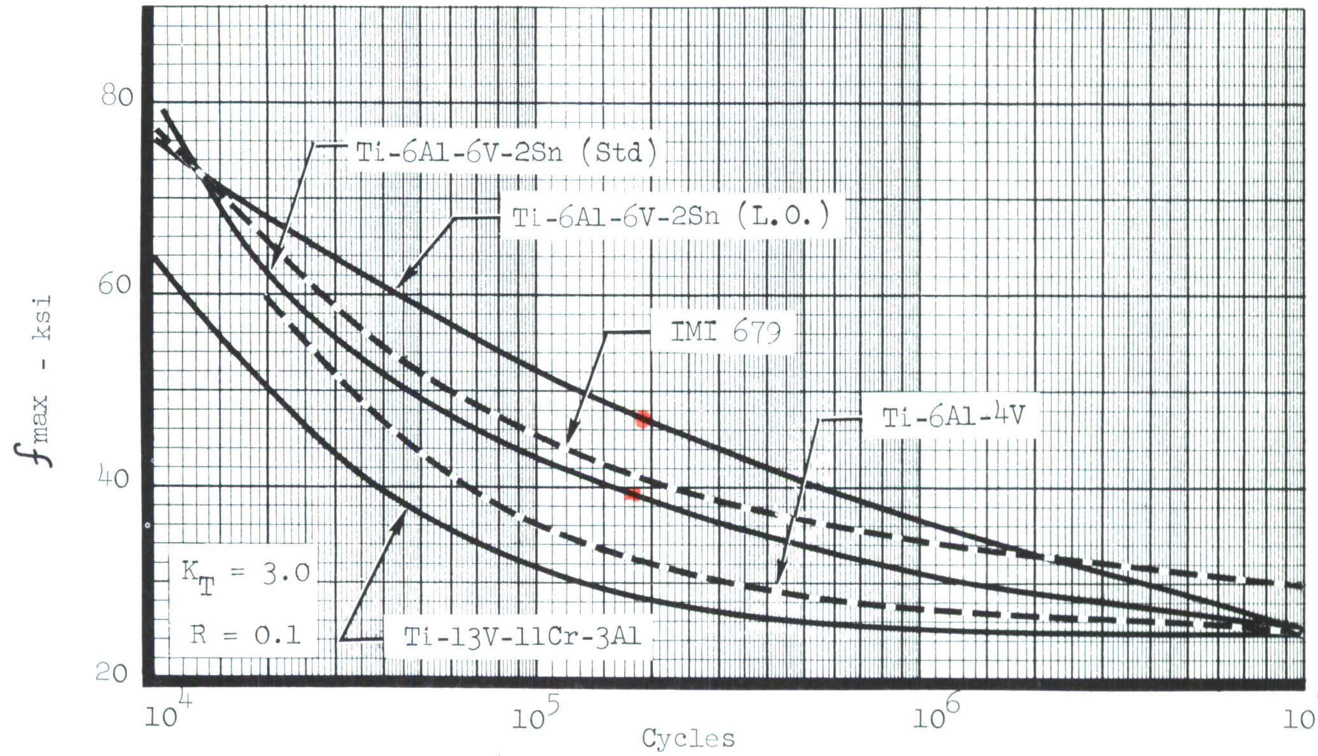


Figure 7. Comparison of Room Temperature Notched Fatigue Properties

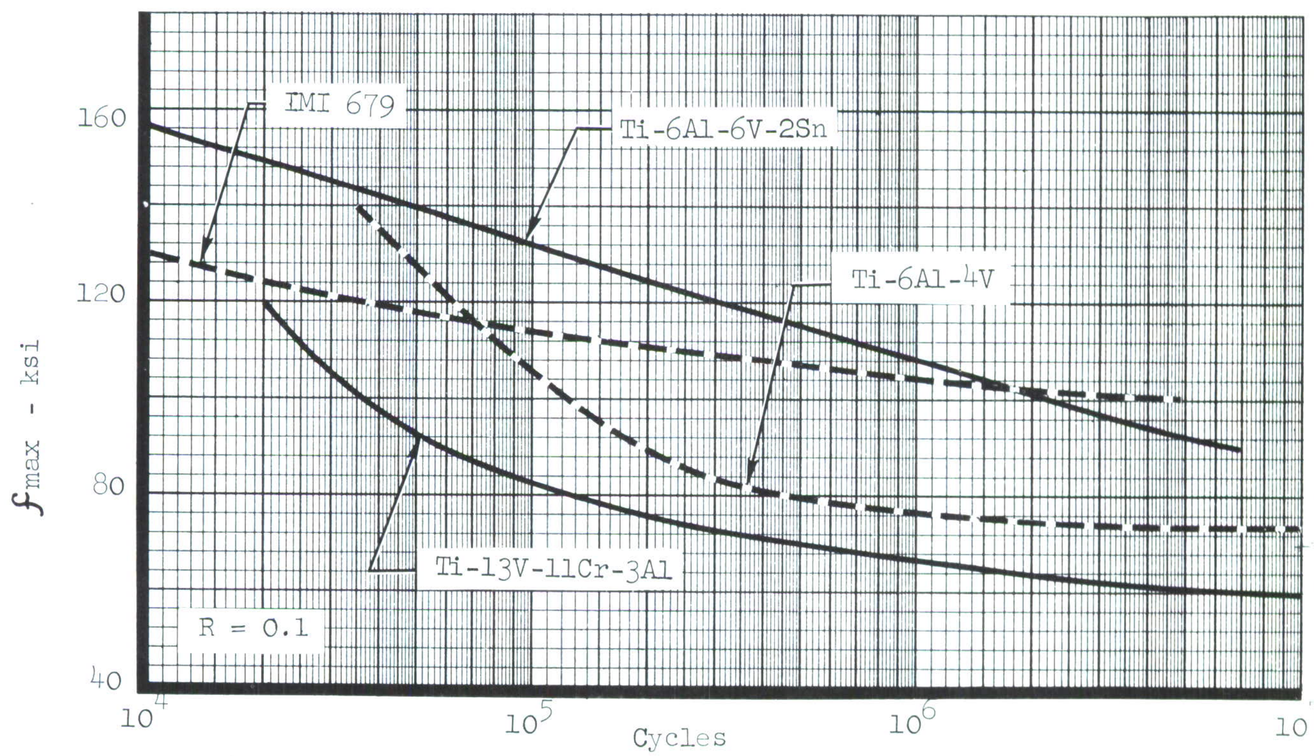


Figure 8. Comparison of Room Temperature Smooth Fatigue Properties

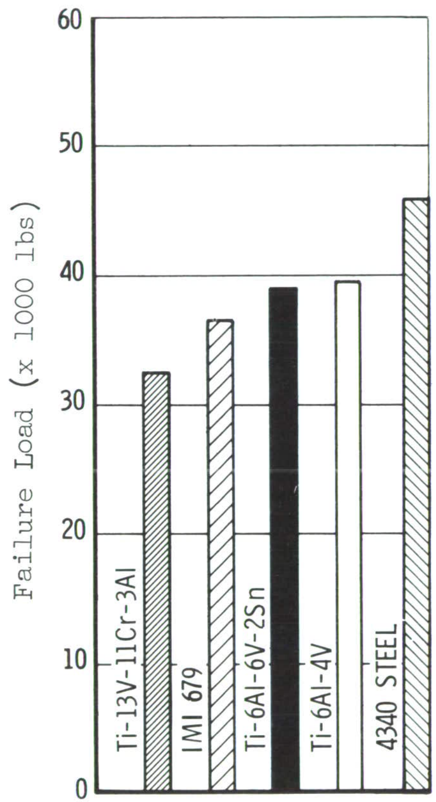


Figure 9. Comparison of Forging Static Strength

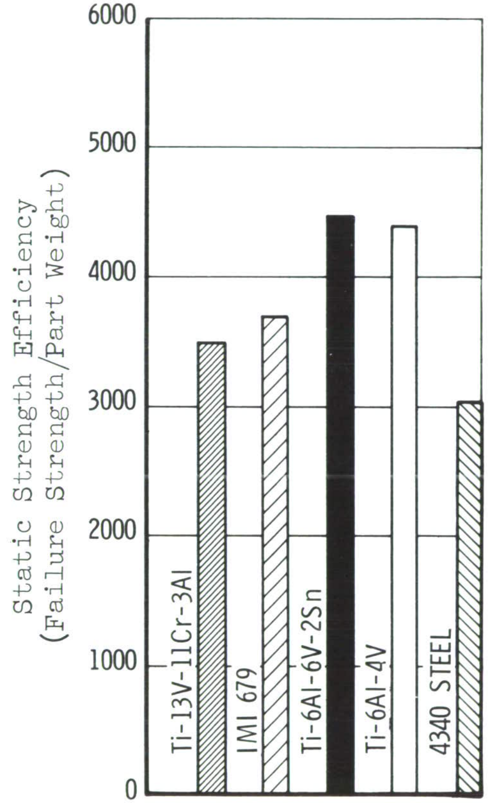


Figure 10. Comparison of Static Strength Efficiency

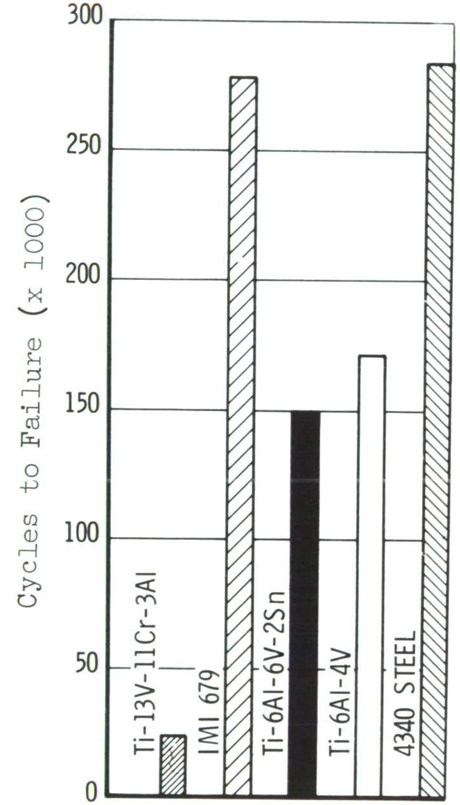


Figure 11. Comparison of Forging Spectrum Fatigue Strength

Section III

PROGRAM FORGINGS

The rough forging configuration used for this evaluation is the modified F-104 fuselage ring fitting. This configuration is identical to the forging used in the program described in Reference 1 which permits direct comparisons of material properties and full-scale test results for four titanium alloys. Since the selection of a representative forging was of major importance to the program, the background information on which this selection was based is presented below.

CONFIGURATION SELECTION

The production, closed-die, F-104 fuselage ring fitting used in this program was originally selected for evaluation in the program described in Reference 1 as being representative of typical airplane forging design. The fuselage ring fitting joins the forward beam of the vertical stabilizer to the aft fuselage structure. Figure 12 shows an actual installation of the forging in the aft fuselage of an F-104. The production part is made from a 4340 alloy steel forging, heat treated to an ultimate tensile strength of 180-200 ksi. Since this part must sustain high loads and reversals, it provides for a critical comparison of material serviceability.

The rough forging from which the titanium part was machined (Figure 13) represents a modification of the steel counterpart to include broader overall tolerances and a heavier center section of approximately 5 x 6 inches cross section. This modified configuration represents the conditions that can be expected to be of importance in most forged parts. The heavy section provided a test of the forging procedures needed to produce the fine grain and metallurgical structure required to meet specified properties and the inherent hardenability of the alloys. The webs and flanges in the balance of the forging provide substantial metal flow and transitions from thick to thin sections. In the titanium forgings, maximum loads were sustained by the structure originally forged in the heaviest section. Thus, the data obtained from evaluation of the modified forging are considered to have wide use in the design application of light and heavy section titanium alloy forgings.

It should be pointed out that while the selected forging design is well suited for the program in that it provides the required large section size, it does not represent current tolerances that can be achieved in titanium parts. It is possible to design and produce a forging which would conform much more closely to the final machined shape.

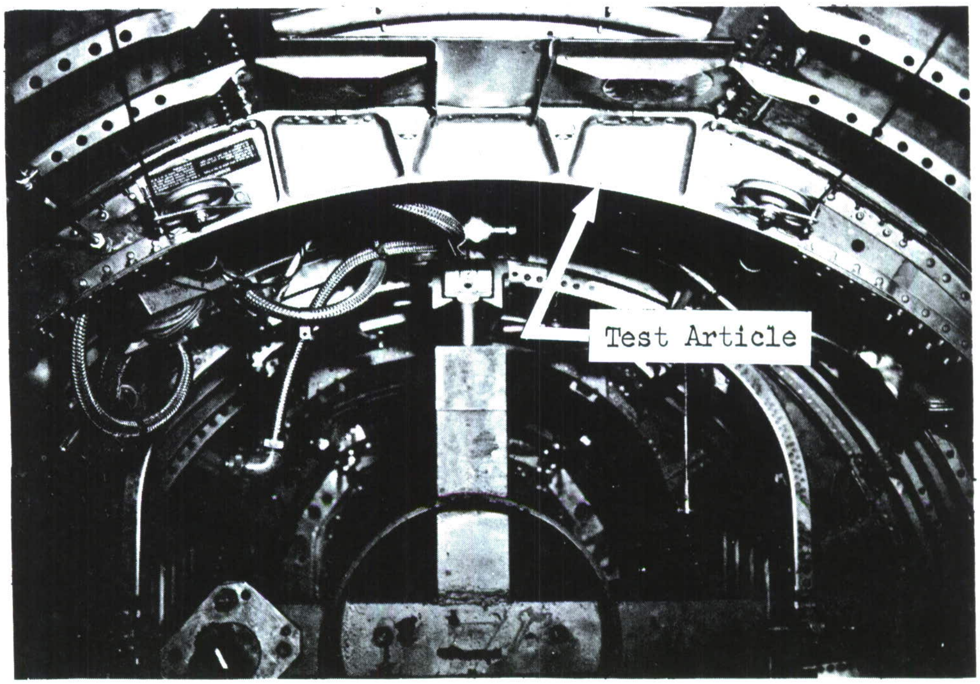


Figure 12. View of Interior of Aft Fuselage on F-104 Showing Forward Fuselage Ring Fitting

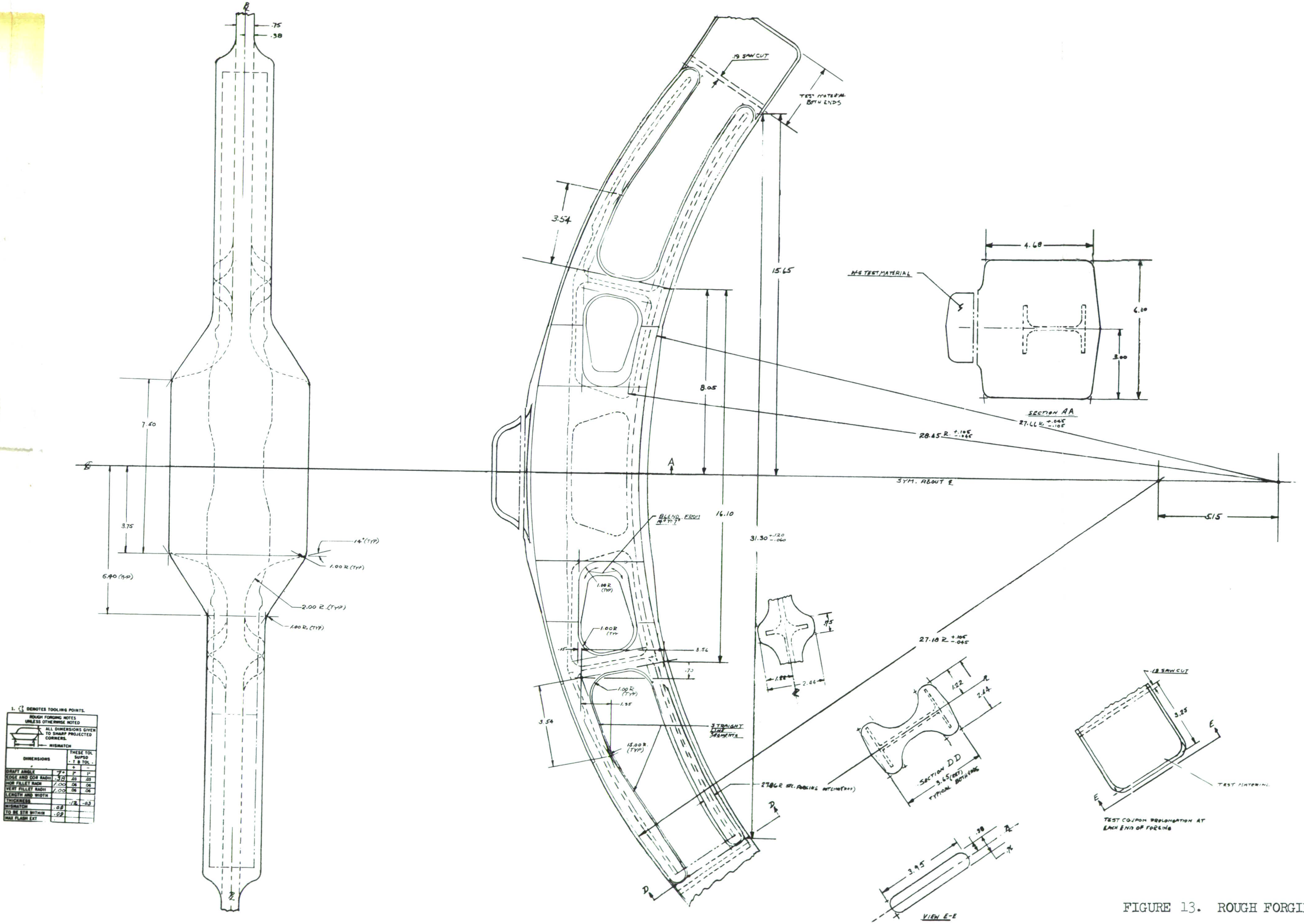


FIGURE 13. ROUGH FORGING FUSELAGE RING

PRODUCTION

Production procedures used in this contract are identical to those used in the previous program (Ref. 1) so that a comparison of properties could be made with data from that program.

All billet stock was supplied by Titanium Metals Corporation. Test data on chemical analysis, mechanical properties of billet material, and mechanical properties of upset forged material are given in Appendix I. Additional billet property data obtained by the Wyman-Gordon Company are also given in Appendix I along with macro-etched sections showing grain structure for billet stock of Ti-6Al-4V and IMI 679.

Starting billet size in all materials was approximately 7 x 7 x 13 inches. The initial forging operation was cross working. The 13-inch billet stock was upset to a 7-inch height. The stock was then cross worked in each of the other axes and returned to the original shape. The objective of this work was to obtain additional working in the billet, since the final reduction in the forging heavy section was limited. The stock was next cogged to the pre-bent shape. The pieces were subsequently sandblasted, tooled, put through the bending operation, and then finish forged. A view of a finished forging is shown in Figure 14. Each forging was subjected to ultrasonic inspection, and no defects were found.

Additional details related to forging production are given in Appendix II. Longitudinal and transverse macro-sections taken through the billets are also shown in this appendix.

The machined part drawing is shown in Figure 15. As pointed out earlier, the titanium forgings were purposely modified to contain a liberal dimensional envelope on all surfaces plus a heavy center section. This modification necessitated a substantial amount of metal removal to obtain finished parts. Numerical tape control machining was selected as the most economical means of machining the four titanium parts for the full-scale tests. Prior to machining of each forging, a slab approximately 1 x 7 x 5 inches was removed from each side of the heavy center section in a direction parallel to the parting plane. This material was used for tool tryout and certain material property tests.

The IMI 679 rough forgings were heat treated in full section size at Wyman-Gordon. Machining to final dimensions on these forgings proceeded directly after the slabbing operation. However, with the Ti-6Al-4V forgings it was necessary to reduce the section size at time of heat treatment in order to achieve the desired strength level. To provide the proper section size for heat treatment, the two Ti-6Al-4V parts for full-scale test were rough machined to a maximum thickness of 2-1/2 inches. A rough machined Ti-6Al-4V part after heat treat and pickling is shown in Figure 16. Completed titanium parts are shown in Figure 17.

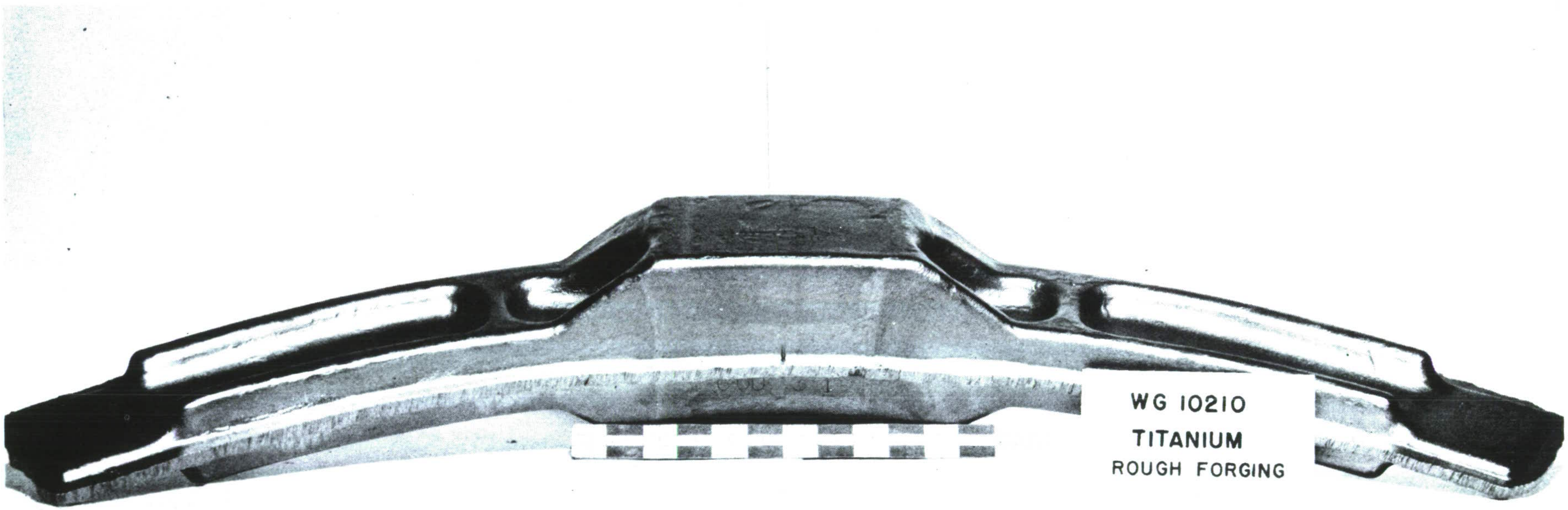


Figure 14. Finish Forged Piece

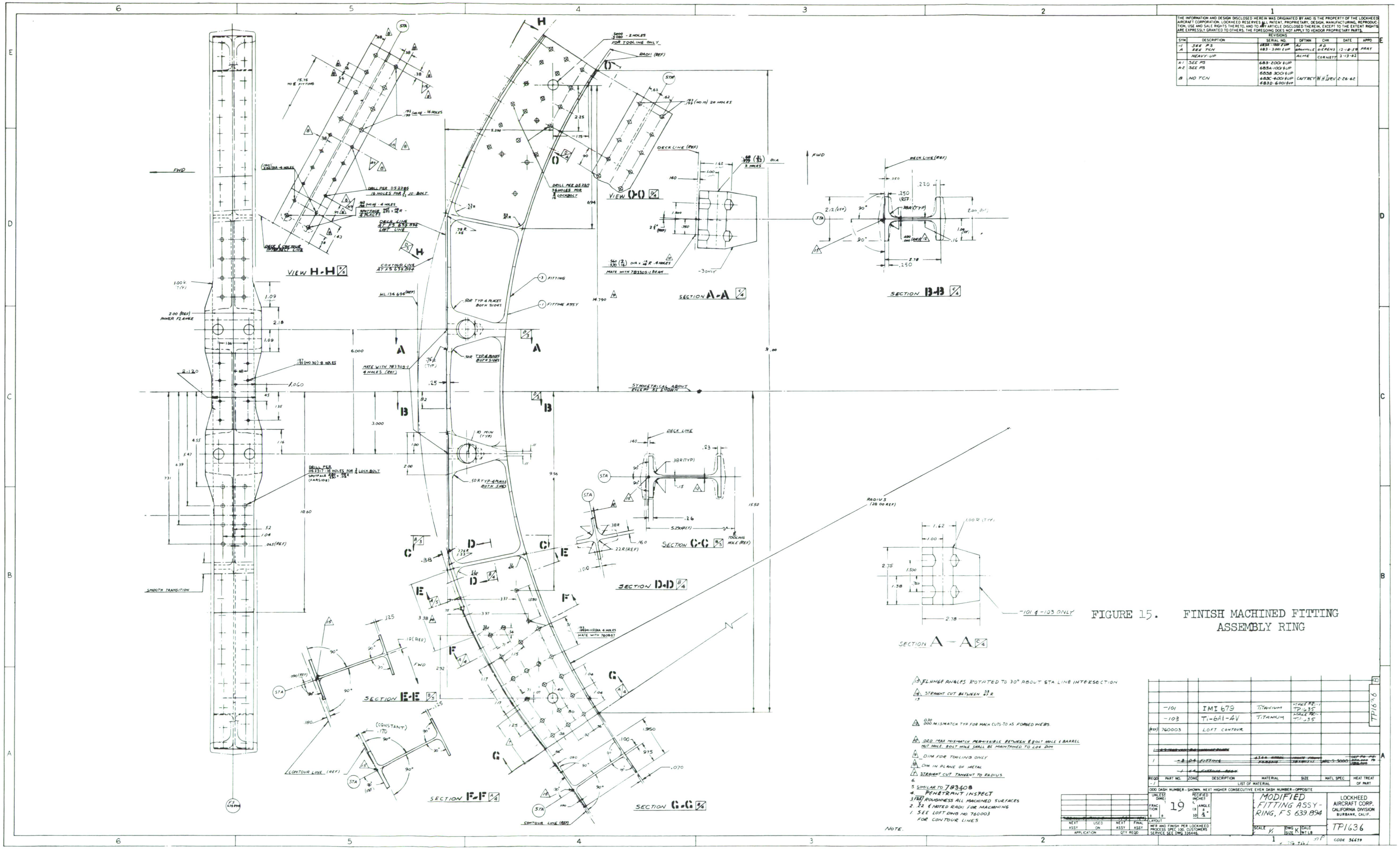


FIGURE 15. FINISH MACHINED FITTING ASSEMBLY RING

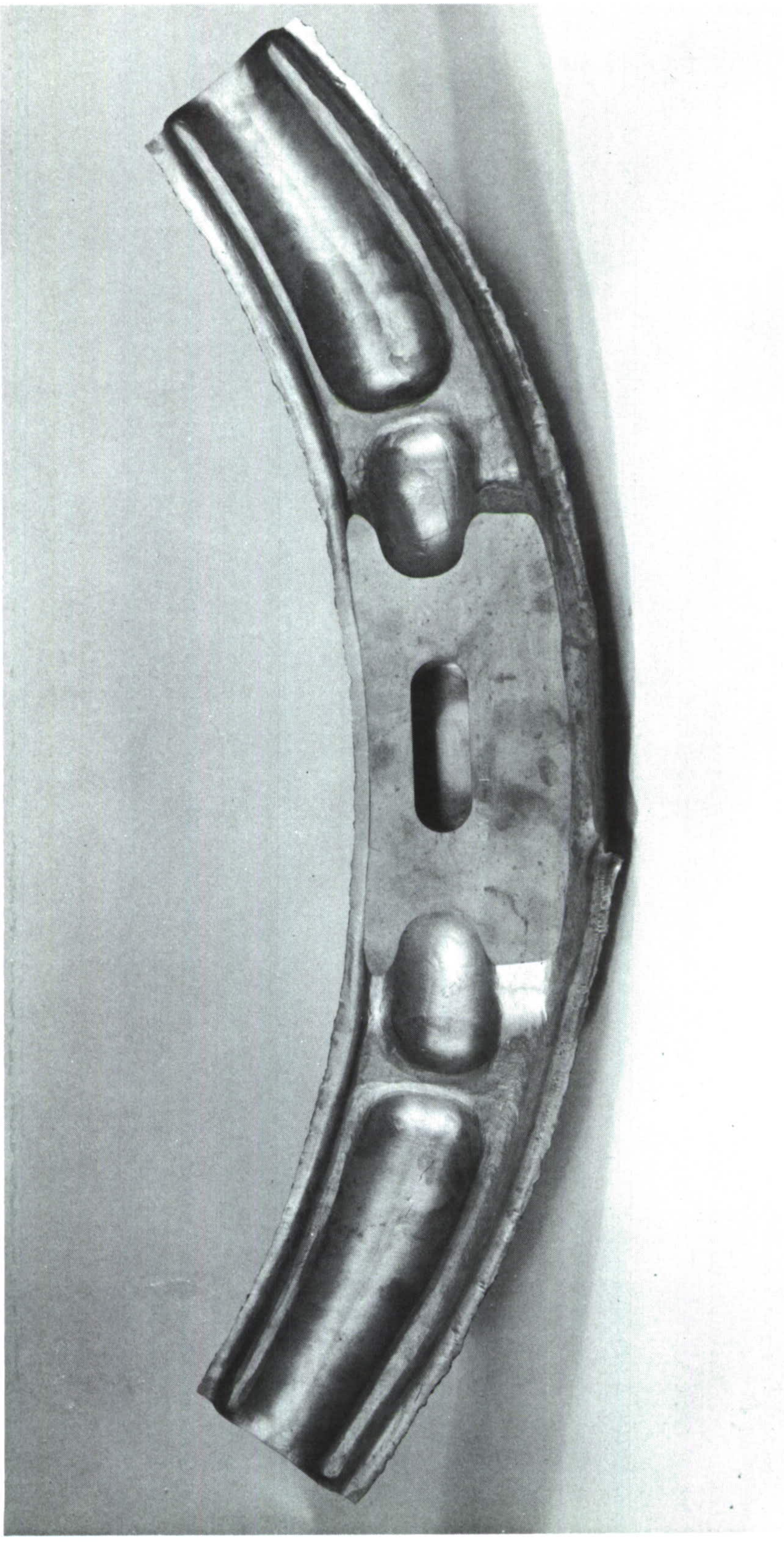
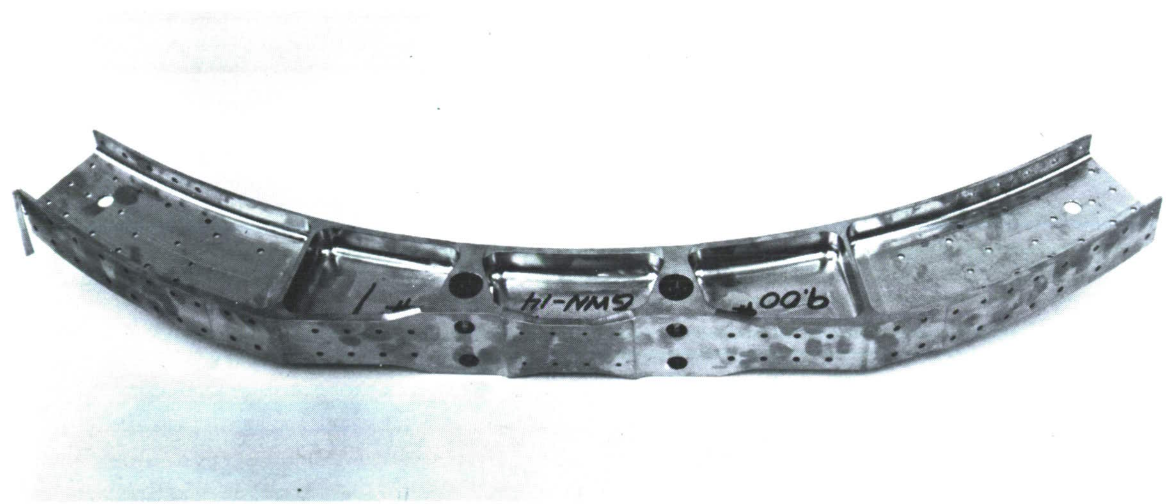
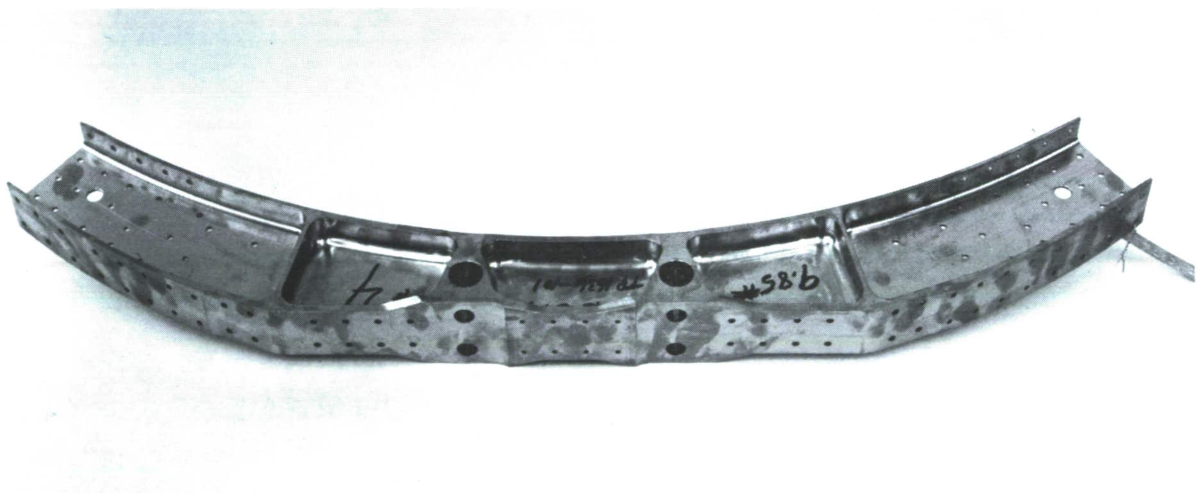


Figure 16. Ti-6Al-4V Rough Machined Part



Ti-6Al-4V



IMI 679

Figure 17. Finish Machined Forgings

HEAT TREATMENT

A minimum ultimate tensile strength goal of 145 ksi was selected for both the Ti-6Al-4V and IMI 679 alloys in this program. To achieve this strength level in the Ti-6Al-4V, the forgings were machined to a maximum section thickness of 2-1/2 inches prior to heat treatment. The Ti-6Al-4V was heat treated in accordance with the procedures specified in Specification AMS 4967. The IMI 679 forgings were heat treated in full section size at Wyman-Gordon since data indicated that the IMI 679 was less sensitive to quench rate. The heat treatment given to the IMI 679 was the standard heat treatment recommended by the supplier of this alloy. (2) (3)

The detailed heat treatments used on all four of the forgings in each alloy are shown below.

Alloy	Heat Treatment Procedure
Ti-6Al-4V	1750°F - 1 hour, within 6 seconds water quench, age at 1000°F - 4 hours, air cool
IMI 679	1650°F - 1 hour, fan cool, age at 930°F - 24 hours, air cool.

Heat treatment varification tests were performed by Wyman-Gordon on material forged integrally with the forgings and removed for test. Location and orientation of the integral forged test material is shown in Figure 18. The test data obtained from this material are presented in Tables 1 and 2.

The heat treat varification tests conducted by Wyman-Gordon on the IMI 679 showed very uniform properties from the center section to the flange. The test data obtained from the integrally forged material were representative and in good agreement with the data obtained from the forging.

The Ti-6Al-4V heat treat varification tests also showed uniform properties from the center section to the flange, but were higher than the Lockheed data. The high properties probably resulted from the smaller quench size of the integrally forged material.

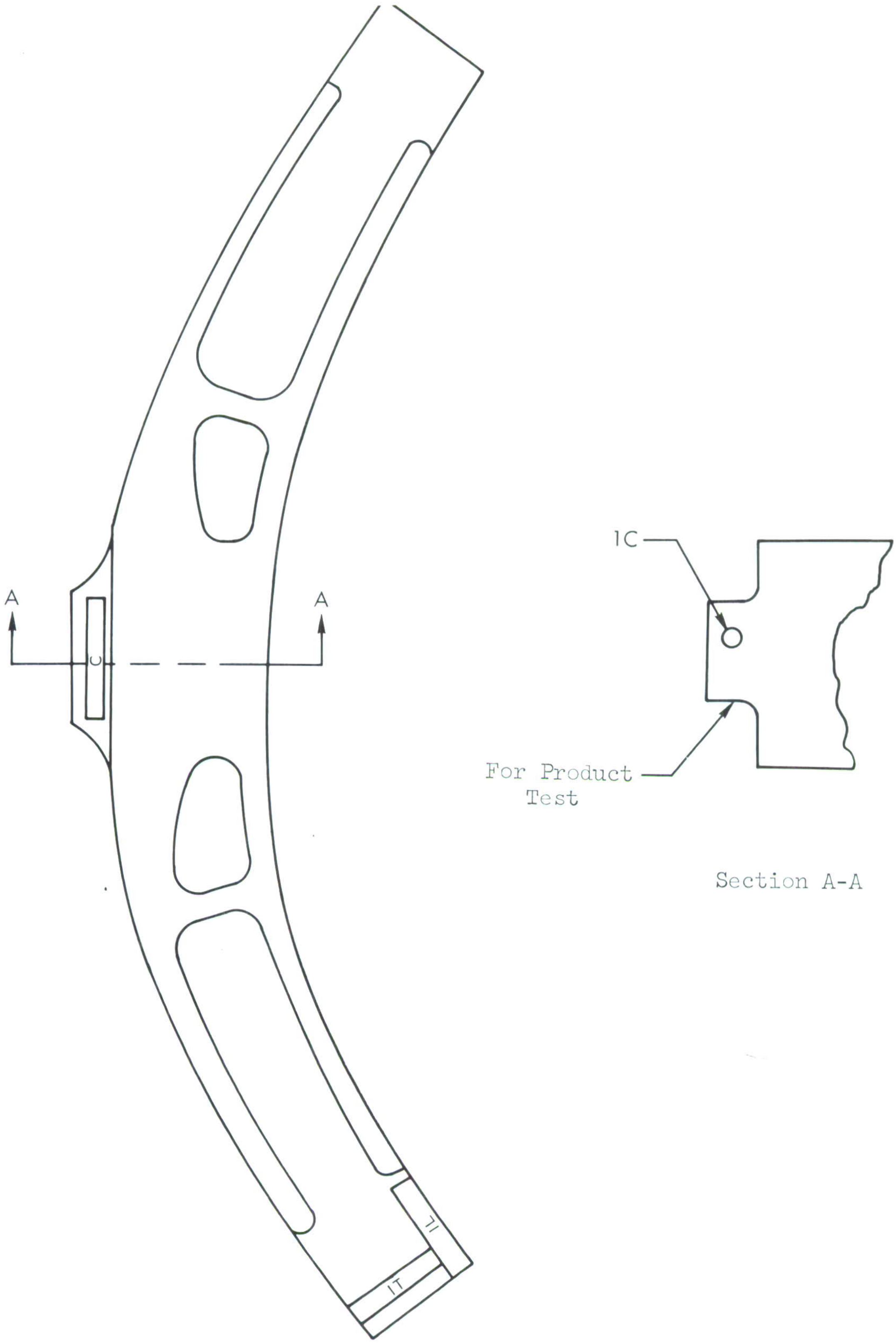


Figure 18. Capability Tests - Integrally Forged Coupons

TABLE 1. PRODUCT TEST RESULTS Ti-6Al-4V TMCA HEAT D-7976 MATERIAL CUT FROM FORGING, HEAT TREATED AS COUPONS (1)

Forging Number	Spec. No.	Location	Ultimate Tensile Strength ksi	Yield Strength 0.2% ksi	Elong. % 1 in.	R.A. %
1	1L	End Pad Long.	178.0	164.0	10.0	29.9
	1T	End Pad Trans.	170.6	156.0	11.0	33.8
	1C	Center Pad Long.	168.0	154.0	10.5	31.8
2	1L	End Pad Long.	171.4	157.0	13.0	35.7
	1T	End Pad Trans.	173.6	158.0	11.0	35.7
	1C	Center Pad Long.	169.6	154.8	10.5	32.7
3	1L	End Pad Long.	181.6	169.2	10.5	35.7
	1T	End Pad Trans.	174.0	160.8	11.5	34.4
	1C	Center Pad Long.	168.4	155.8	10.5	34.4
4	1L	End Pad Long.	176.2	163.4	12.0	38.2
	1T	End Pad Trans.	168.0	153.8	13.5	45.0
	1C	Center Pad Long.	170.0	158.0	8.5	23.1
			172.4	158.7		

(1) Heat Treatment:
Solution Treated 1750°F (1 hour) W.Q.
Aged 1000°F (4 hours) A.C.

TABLE 2. PRODUCT TEST RESULTS - IMI-679 - TMCA HEAT 8427 (1)
ALL SAMPLES WERE INTEGRAL WITH FORGINGS AT TIME OF HEAT TREATMENT

Forging Number	Spec No.	Location	Ultimate Tensile Strength ksi	Yield Strength 0.2% ksi	Elong. % 1 in.	R.A. %
1	1L	End Pad Long.	152.4	134.0	15.0	46.7
	1T	End Pad Trans.	149.0	134.0	16.0	46.1
	1C	Center Pad Long.	146.4	131.2	15.0	37.6
2	1L	End Pad Long.	153.0	134.0	15.0	47.8
	1T	End Pad Trans.	146.2	131.6	16.0	43.1
	1C	Center Pad Long.	150.0	133.6	13.5	36.3
3	1L	End Pad Long.	153.8	134.6	15.0	43.7
	1T	End Pad Trans.	146.8	131.6	14.5	45.5
	1C	Center Pad Long.	150.0	131.6	14.5	42.5
4	1L	End Pad Long.	152.0	134.2	15.0	46.1
	1T	End Pad Trans.	150.0	132.0	15.0	39.5
	1C	Center Pad Long.	148.0	130.0	13.5	39.5

149.8 132.5

(1) Heat Treatment
Solution Treated 1650°F (1 hour) Fan Cool
Aged 930°F (24 hours) Air Cool

Section IV

MATERIAL PROPERTY EVALUATION

This section presents the material property evaluation data, including thermal exposure, environmental delayed failure resistance and metallurgical results. The material property tests were located throughout the forgings in order to evaluate the effects of forging thickness, grain direction, thickness at time of heat treatment, etc. The type of test specimen and location in the various forgings are shown in Figures 19 through 24. Figures 19 through 21 also illustrate the section sizes into which each forging was cut and the specimen identification letters used. All sectioning was accomplished after heat treatment in the IMI 679 and prior to heat treatment in the Ti-6Al-4V alloys.

Details on the test procedures and specimen geometries that were used for each type of mechanical property test are presented in Appendix III. All evaluation procedures were similar to those used in the program described in Reference 1 in order to permit direct comparisons of data from the two programs.

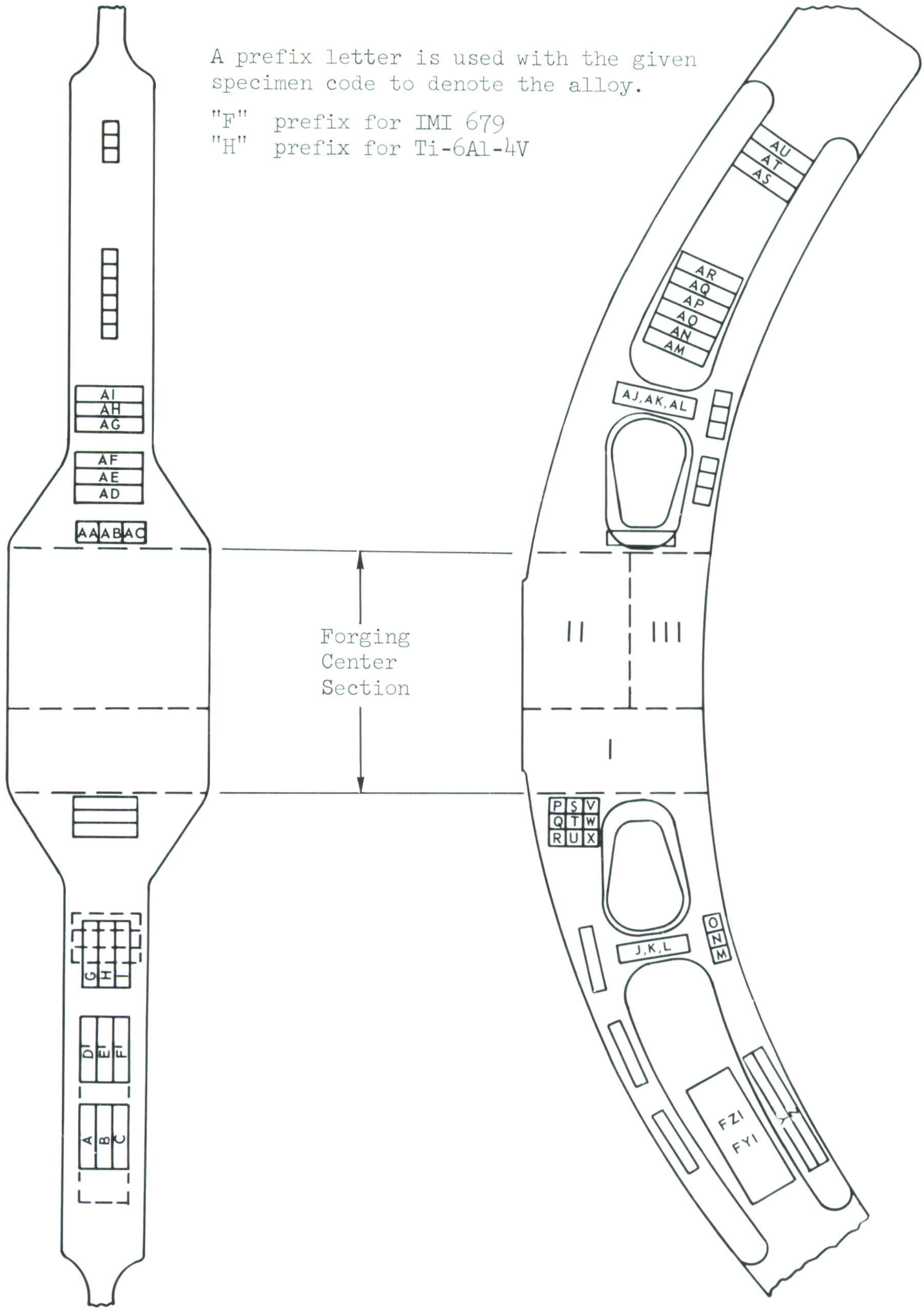


Figure 19. Specimen Layout First Forging IMI 679 and Ti-6Al-4V

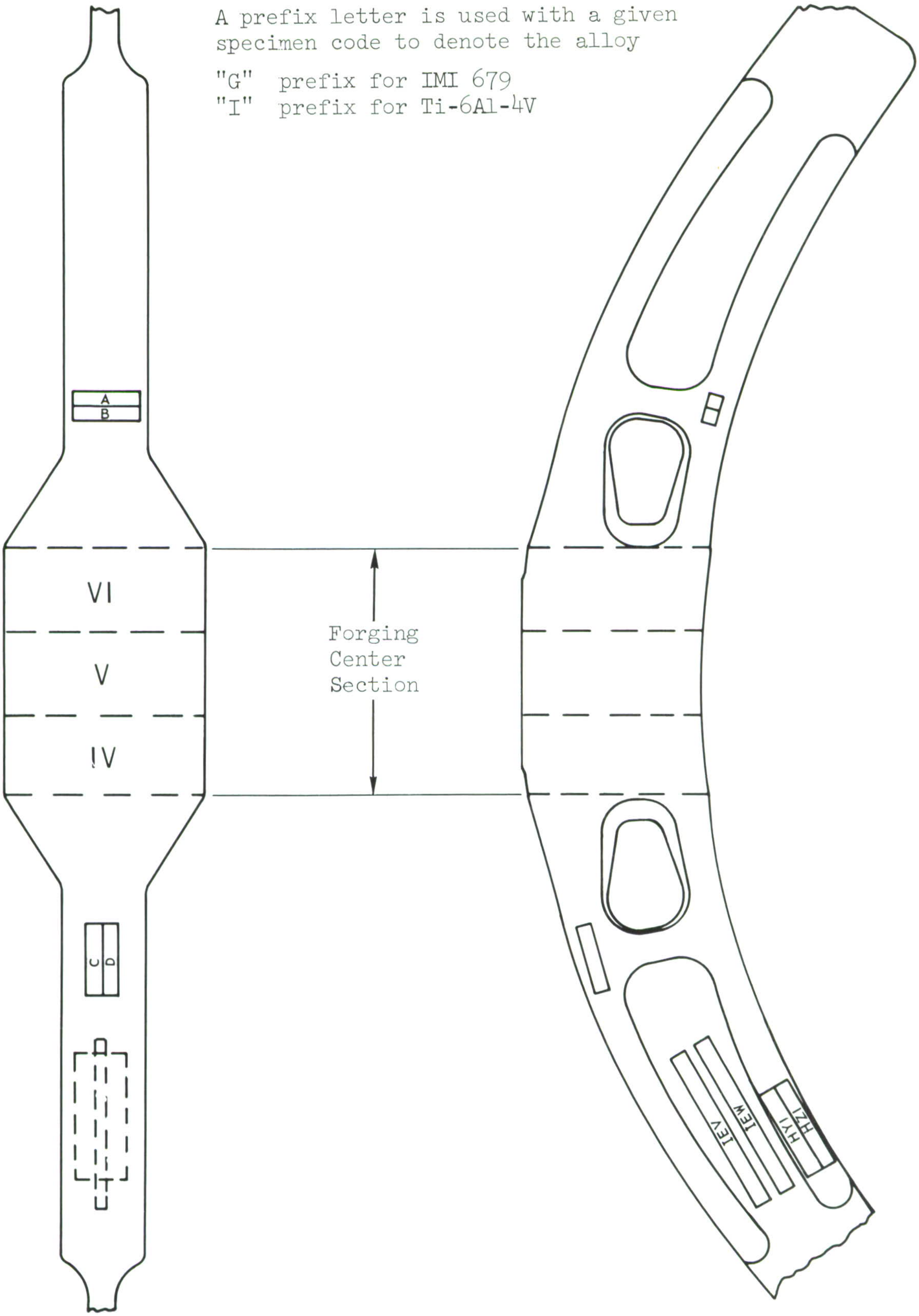


Figure 20. Specimen Layout Second Forging IMI 679 and Ti-6Al-4V

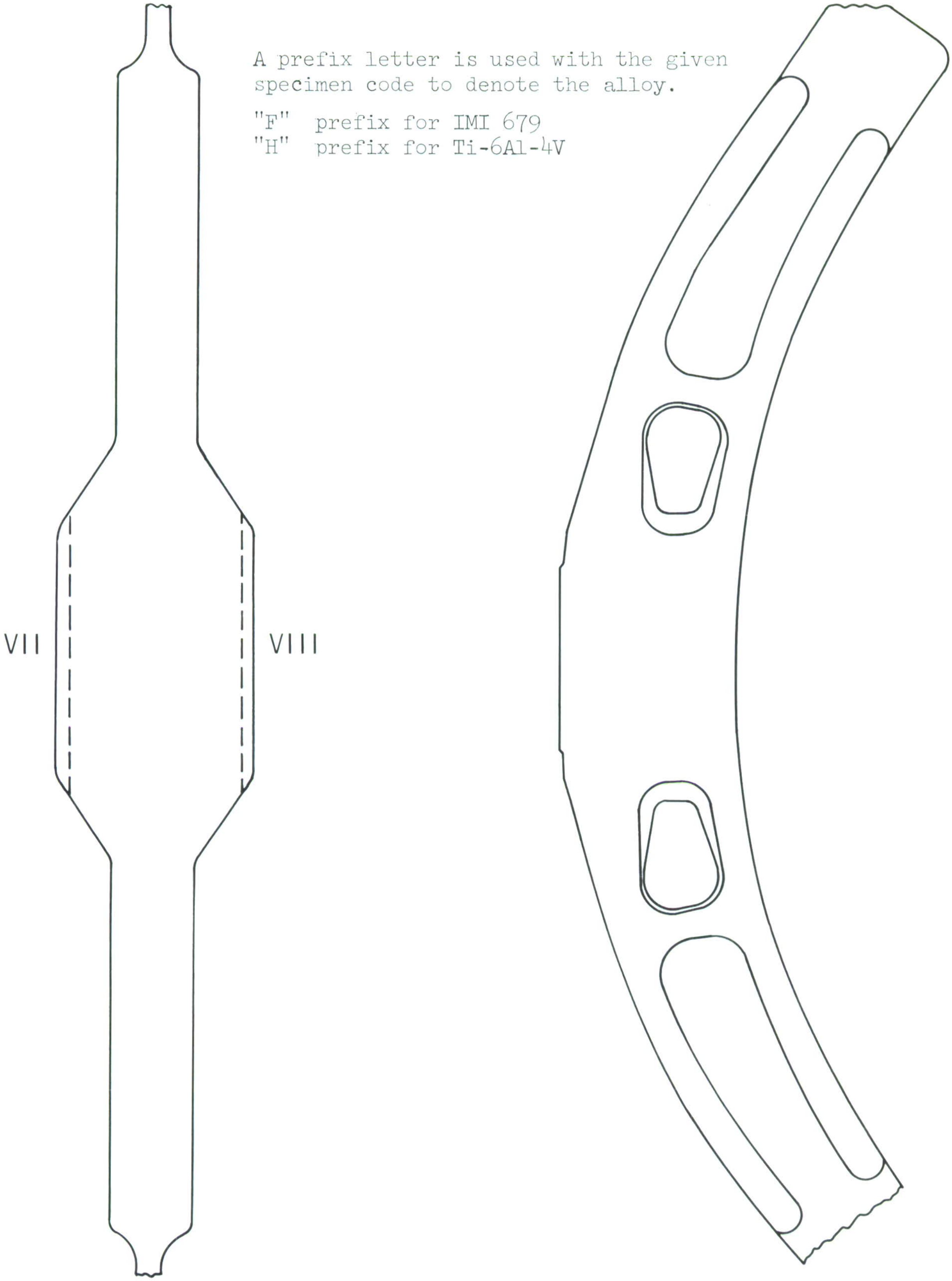
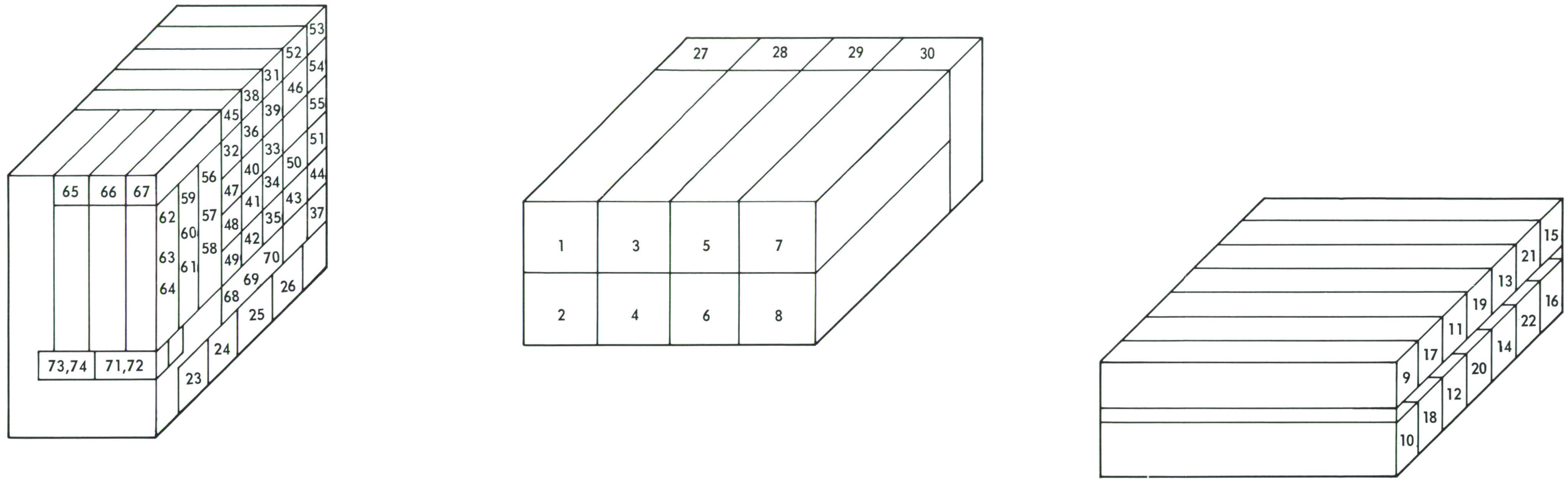


Figure 21. Specimen Layout Third Forging IMI 679 and Ti-6Al-4V



SUB-BLOCK I

TYPE	SPECIMEN NUMBER
23 THROUGH 26	COMPRESSION
39, 43, 46, 50, 52, 53	NOTCHED TENSILE
71 THROUGH 74	SHEAR
ALL OTHERS	TENSILE

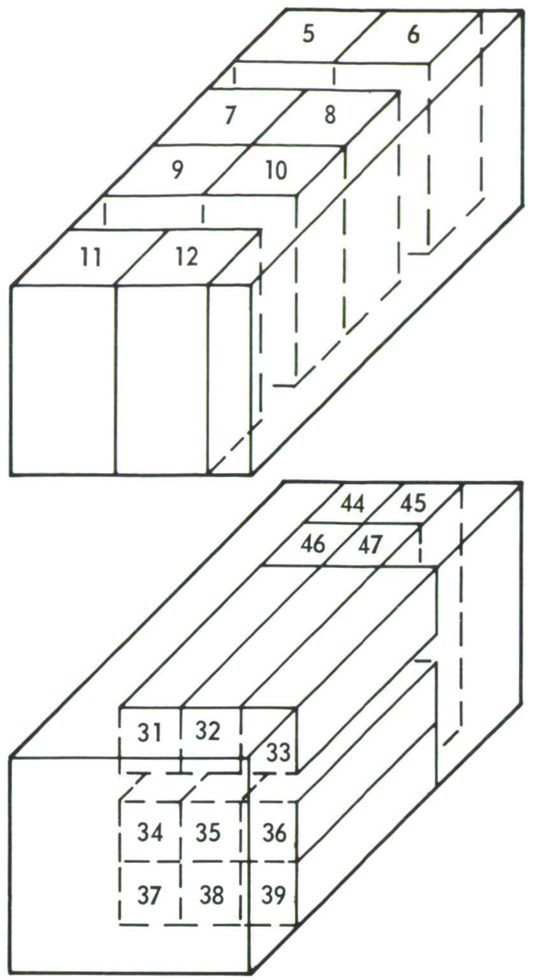
SUB-BLOCK II

SPECIMEN NUMBER	TYPE
1 THROUGH 8	FRACTURE TOUGHNESS
27 THROUGH 30	COMPRESSION

SUB-BLOCK III

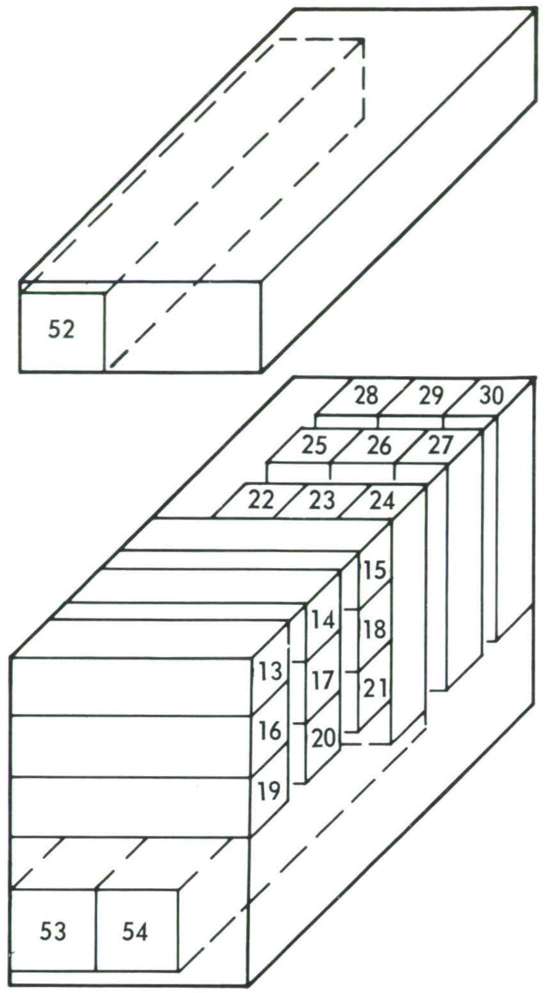
SPECIMEN NUMBER	TYPE
9 THROUGH 22	FATIGUE

Figure 22. Specimen Layout for IMI 679 and Ti-6Al-4V First Forging Center Section



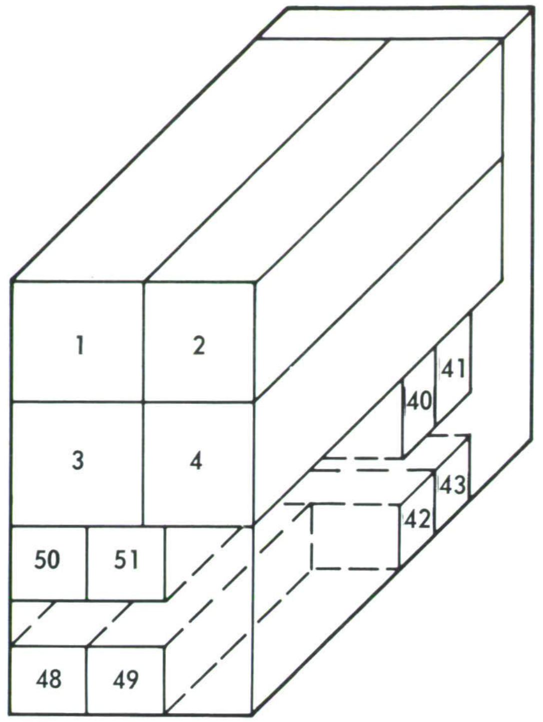
SUB-BLOCK IV

SPECIMEN NUMBER	TYPE
5 THROUGH 12	COMPRESSION
44, 45, 46, 47	NOTCH TENSILE
ALL OTHERS	TENSILE



SUB-BLOCK V

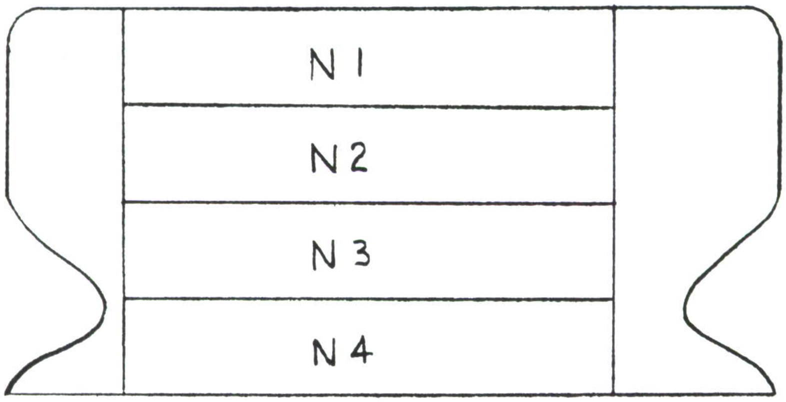
SPECIMEN NUMBER	TYPE
52, 53, 54	FATIGUE
ALL OTHERS	TENSILE



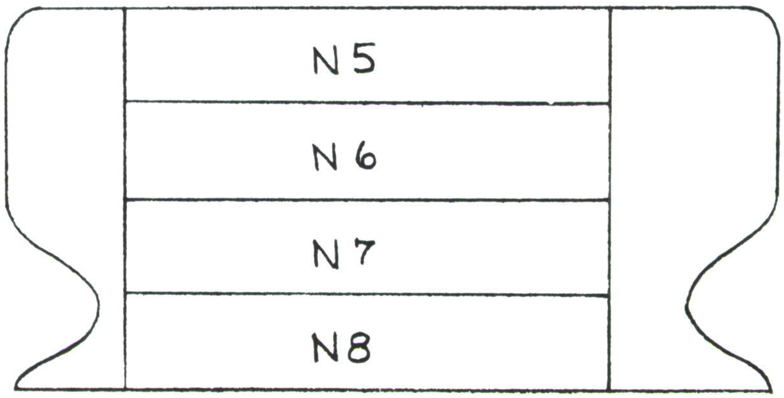
SUB-BLOCK VI

SPECIMEN NUMBER	TYPE
1, 2, 3, 4	FRACTURE TOUGHNESS
ALL OTHERS	NOTCH TENSILE

Figure 23. Specimen Layout for IMI 679 and Ti-6Al-4V Second Forging Center Section



SUB-BLOCK VII



SUB BLOCK VIII

Figure 24. Fatigue Specimen Layout for IMI679 and Ti-6Al-4V
Third Forging Center Section

TENSILE PROPERTIES

Extensive tensile testing was conducted to evaluate variation in tensile properties within the forgings. It was of particular interest to determine tensile property variation in each alloy in locations from edge to center in the forging thick section for all three grain directions and to compare these values with properties obtained in web and flange areas. Variation in properties in each alloy with test temperature and from one forging to another was also investigated to provide data for design.

Tensile data on the Ti-6Al-4V forgings are reported in Tables 3 through 5. In the number two forging of Ti-6Al-4V, the variation of ultimate tensile strength and ductility from edge to center in the forging heavy section is compared for all three grain directions in Figure 25.

This figure shows that tensile strength in the transverse grain direction decreases slightly going from edge locations to center. In the longitudinal grain direction the mid-radius position had the lowest properties. However, total strength range varied less than 10 ksi at any given location, a difference which is not considered significant.

As indicated in Figure 26, tensile yield strength values followed the same pattern as those for ultimate strength.

Tensile strength versus test temperature for all three grain directions in the Ti-6Al-4V alloy is given in Figure 27. Center and edge properties were averaged for each grain direction in this plot. As indicated in Figure 27 very little variation was found in the average tensile ultimate and yield strengths which were obtained at each test temperature.

Tensile property results on the IMI 679 alloy are reported in Tables 6 through 8. The variation in properties with location in the thick section of the IMI 679 forging are shown in Figures 28 and 29. These figures show a trend toward lower values of properties going from edge to center locations for all three grain directions, as might be expected. However, the total property variation in any grain direction was slight, indicating a highly uniform product. Figure 30 presents a plot of tensile strength versus test temperature for IMI 679. Very good agreement in strength values were obtained for all grain directions.

Ductility values as measured by percent elongation and percent reduction in area were excellent at all locations and grain directions in both materials. The lowest values measured at room temperature were 8% elongation and 19% reduction of area in the Ti-6Al-4V forgings and 10.5% elongation and 30% reduction of area in the IMI 679 forgings. Typical values of elongation and reduction in area were substantially higher than these minimums. Testing at -110°F did not significantly affect ductility in either alloy.

Properties in light sections of the forgings can be compared to those obtained in the heavy sections by reviewing the data in Tables 3 through 8. The data indicate that strength and ductility were higher in thin section locations than in heavy center locations in the Ti-6Al-4V forgings. Improved ductility in thinner sections of the Ti-6Al-4V forgings is attributed to the greater amount of work received by the lighter sections. The higher strength of the thinner sections of the forgings is attributed primarily to the faster quench rate at time of heat treatment.

In the IMI 679 forgings, negligible differences were noted between properties in the thin section locations and those in the heavy center section. The range in ultimate tensile strength of Ti-6Al-4V and IMI 679 forged stock was not significantly different from billet stock in either alloy. Elongation, reduction of area, and yield strength in the IMI 679 forgings were improved over those obtained in the billet stock.

Yield strength was lower in Ti-6Al-4V billet than in the forging. This difference is attributed to the larger section size of the billet material at time of heat treatment (e.g., 4-inch-thick billet versus 2 1/2-inch-thick forging). Nevertheless, elongation and reduction in area values appear to be equivalent in the billet and forging.

Typical autographic tensile stress-strain curves for Ti-6Al-4V and IMI 679 are given in Figures 31 and 32, respectively.

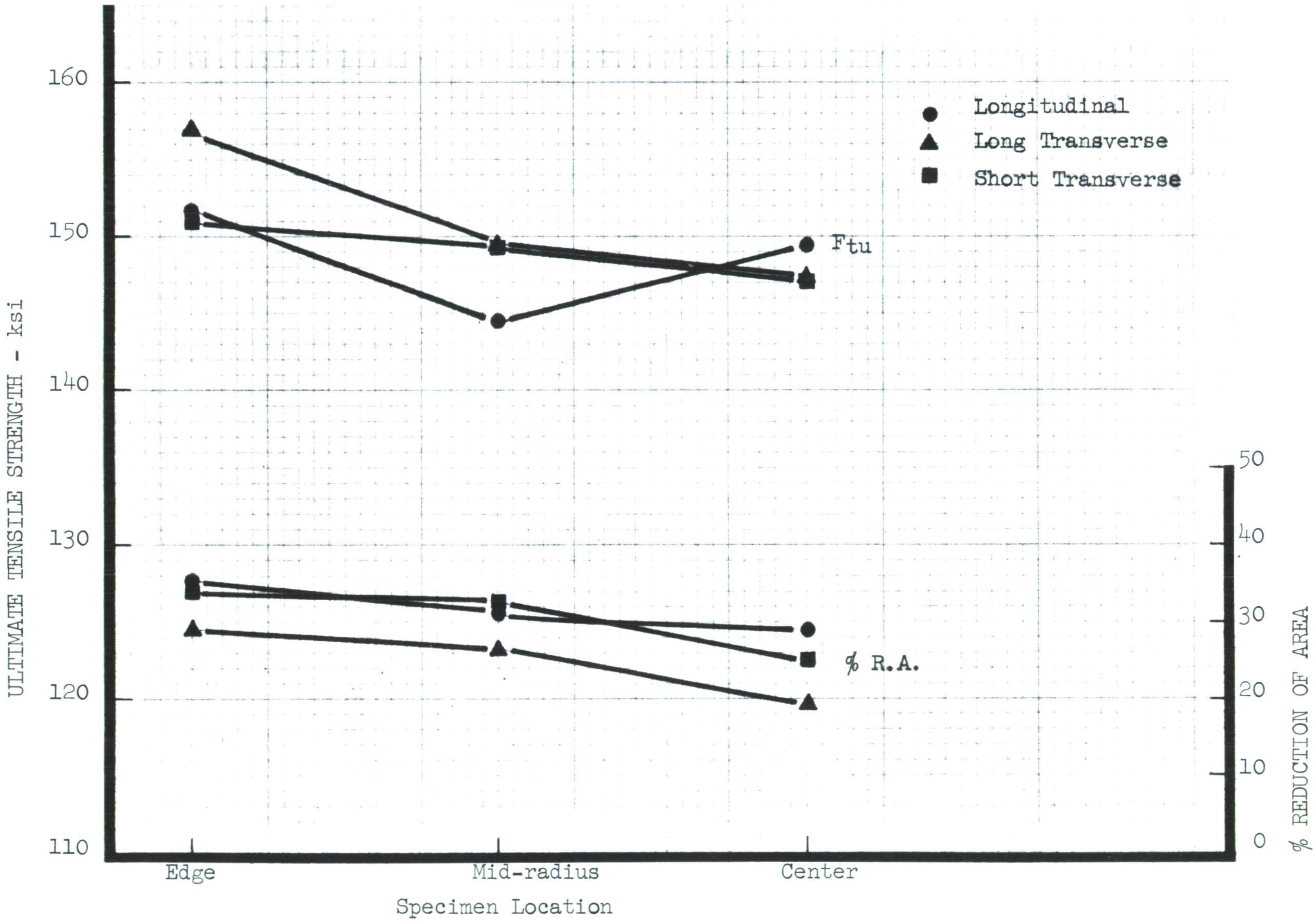


Figure 25. Ti-6Al-4V Room Temperature Tensile Ultimate Strength Forging #2 Center Section

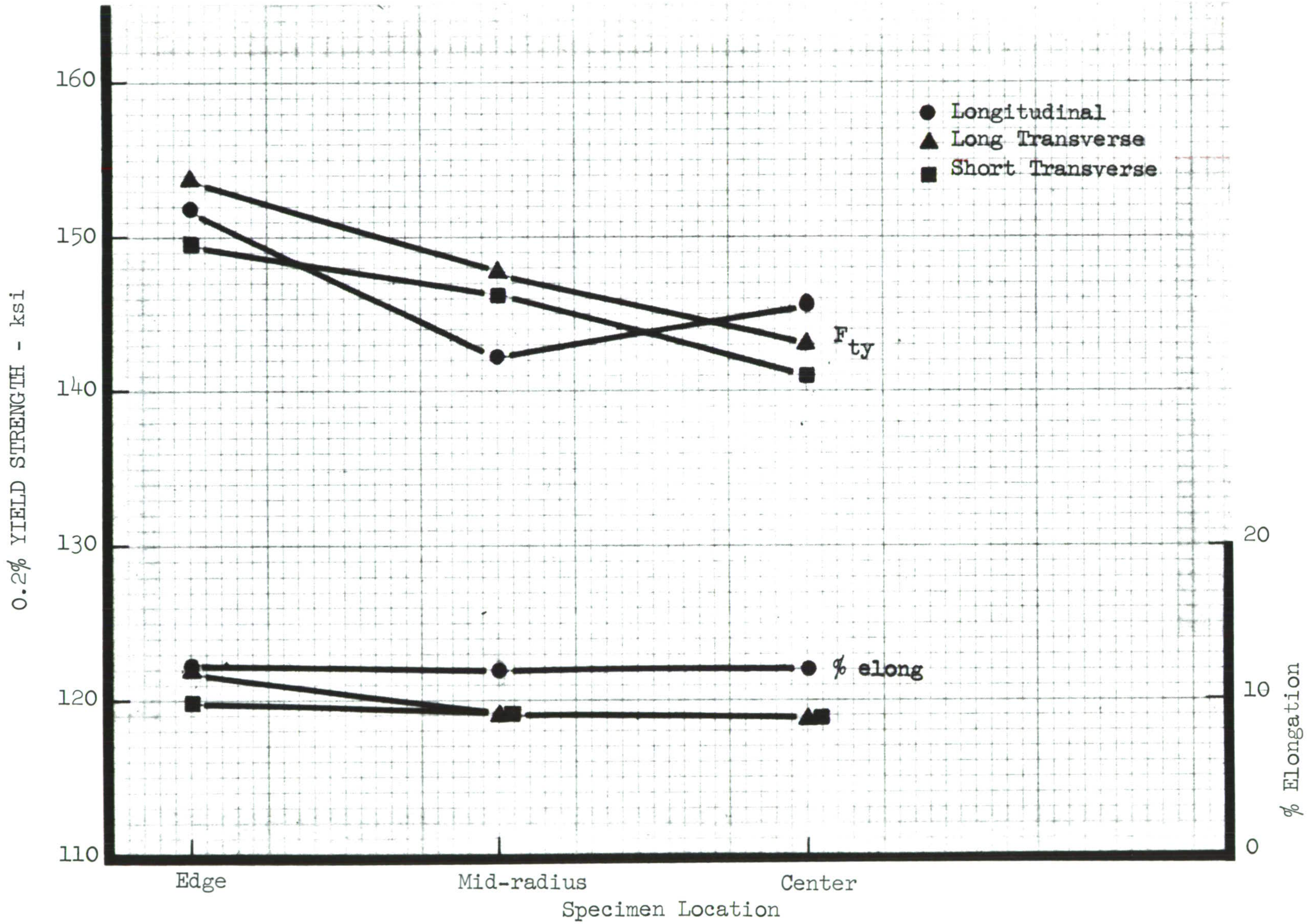


Figure 26. Ti-6Al-4V Room Temperature Tensile Yield Strength Forging #2 Center Section

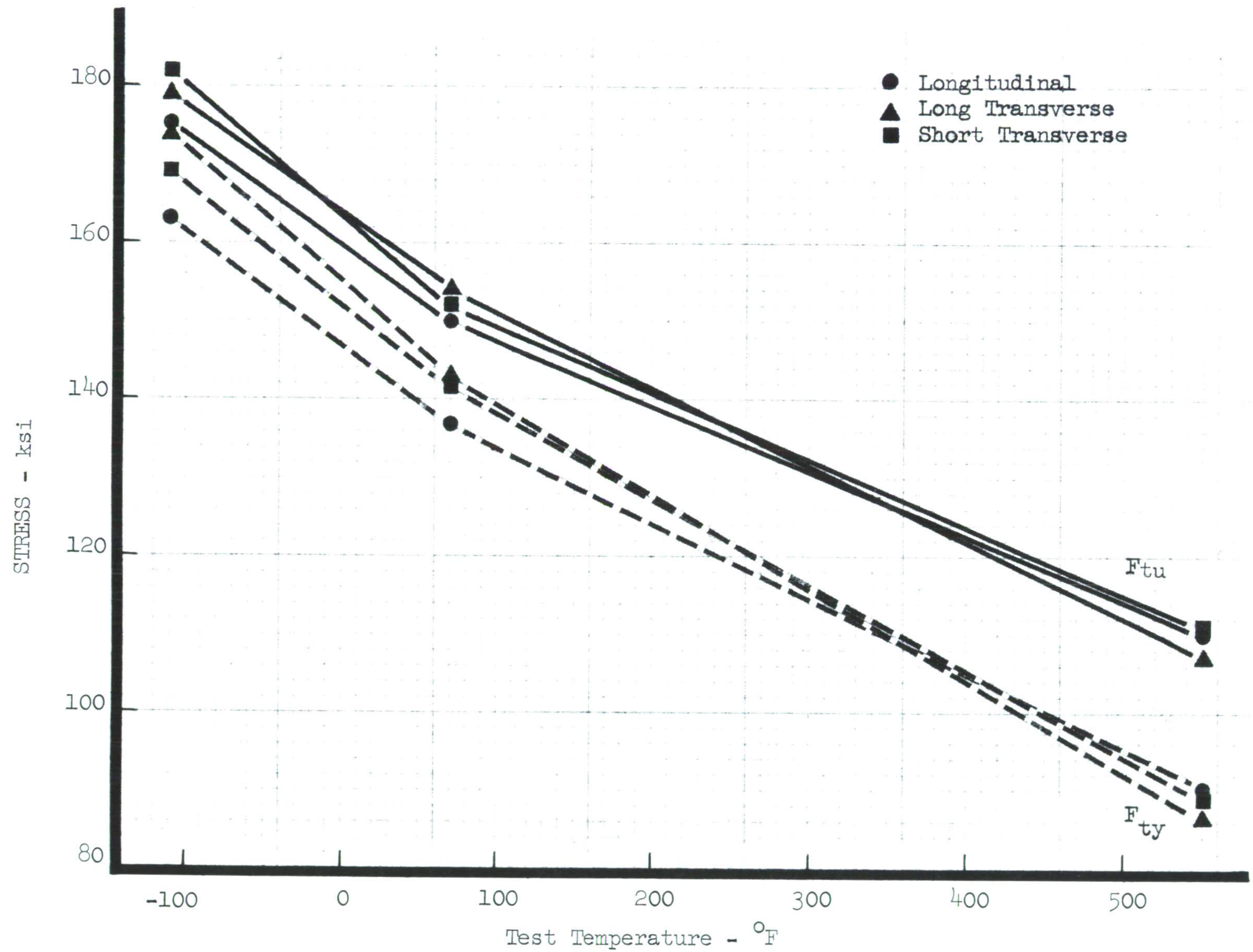


Figure 27. Ti-6Al-4V Smooth Tensile Properties Forging #1 Center Section

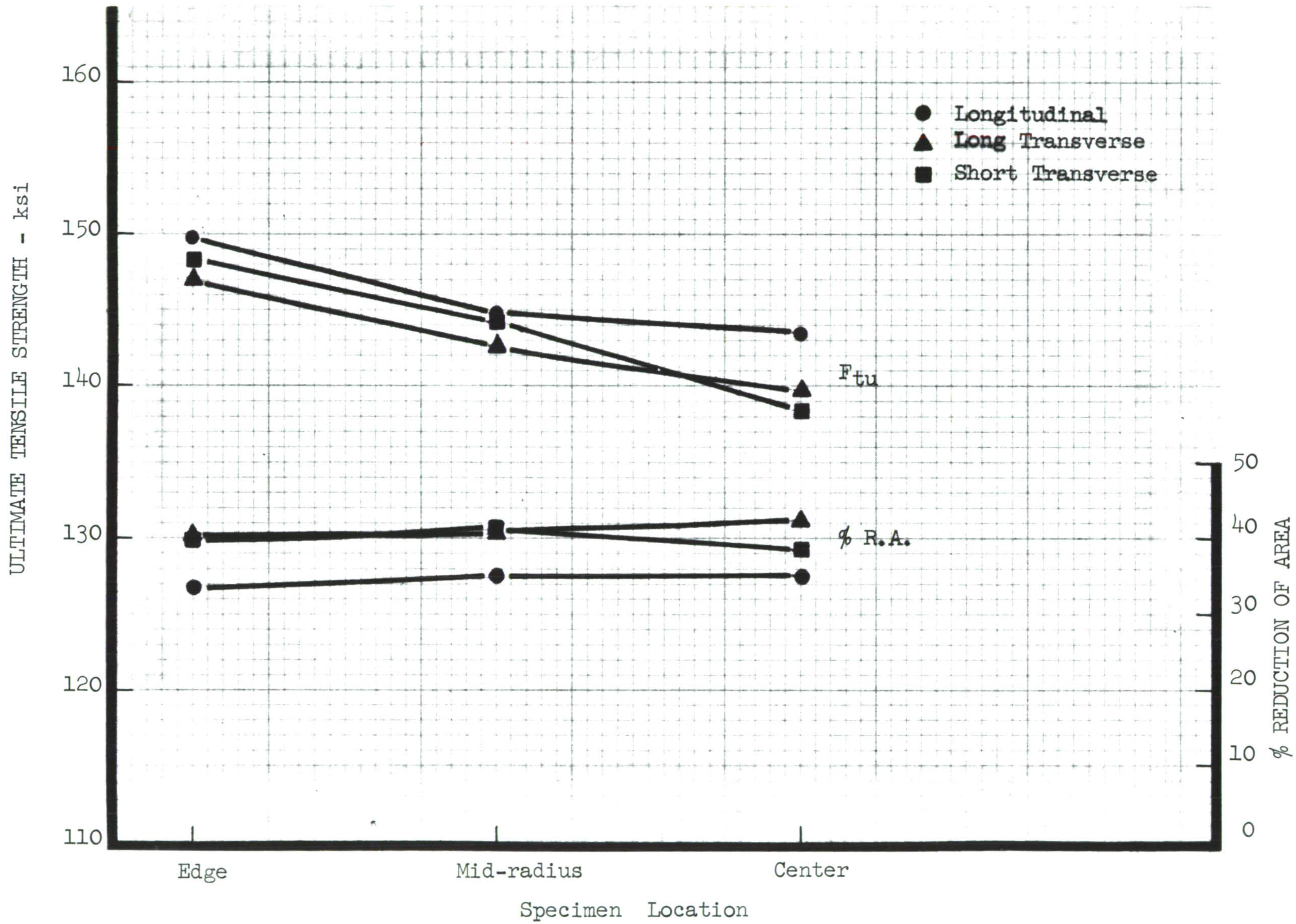


Figure 28. IMI 679 Room Temperature Tensile Ultimate Strength Forging #2 Center Section

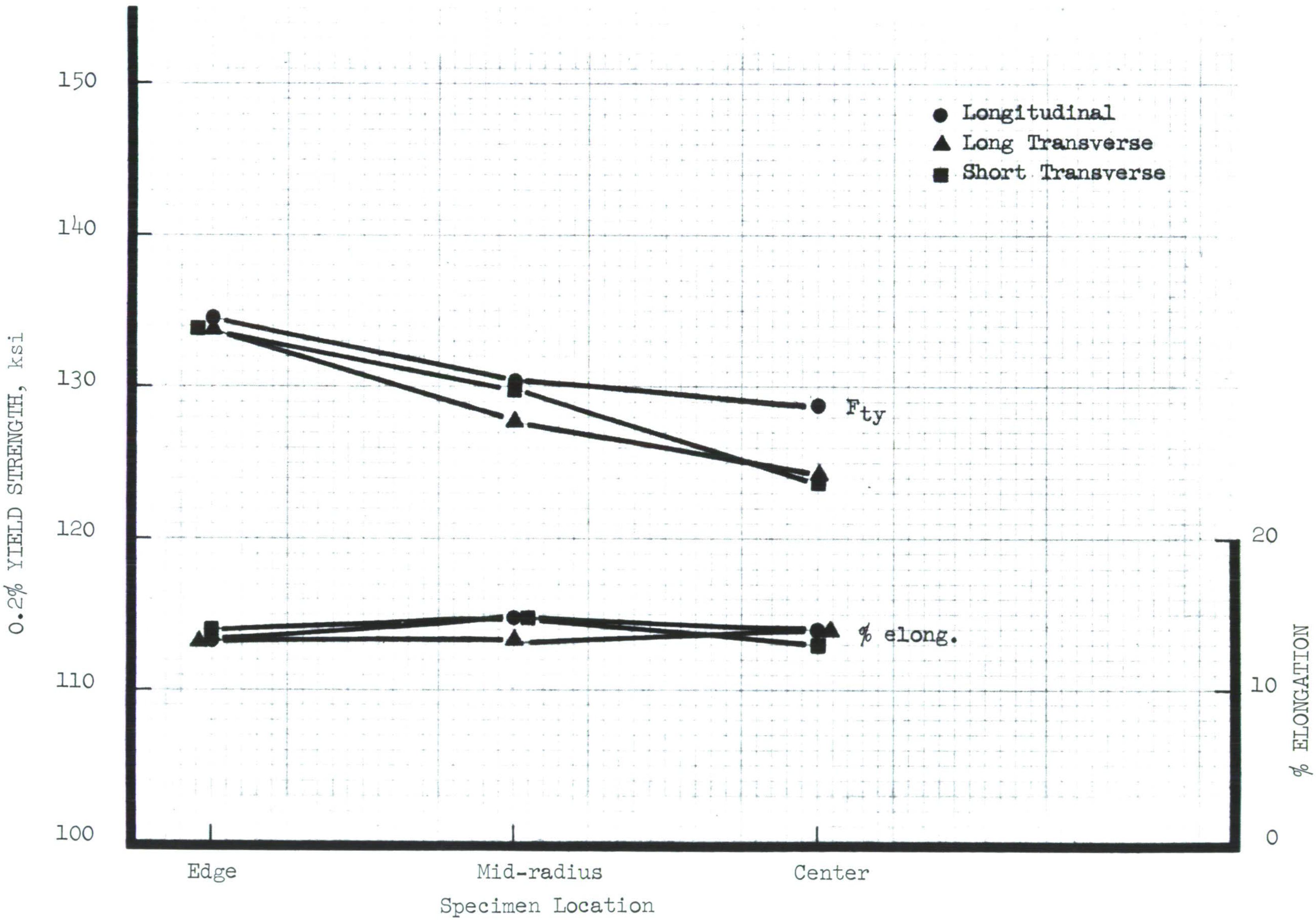


Figure 29. IMI 679 Room Temperature Tensile Yield Strength Forging #2 Center Section

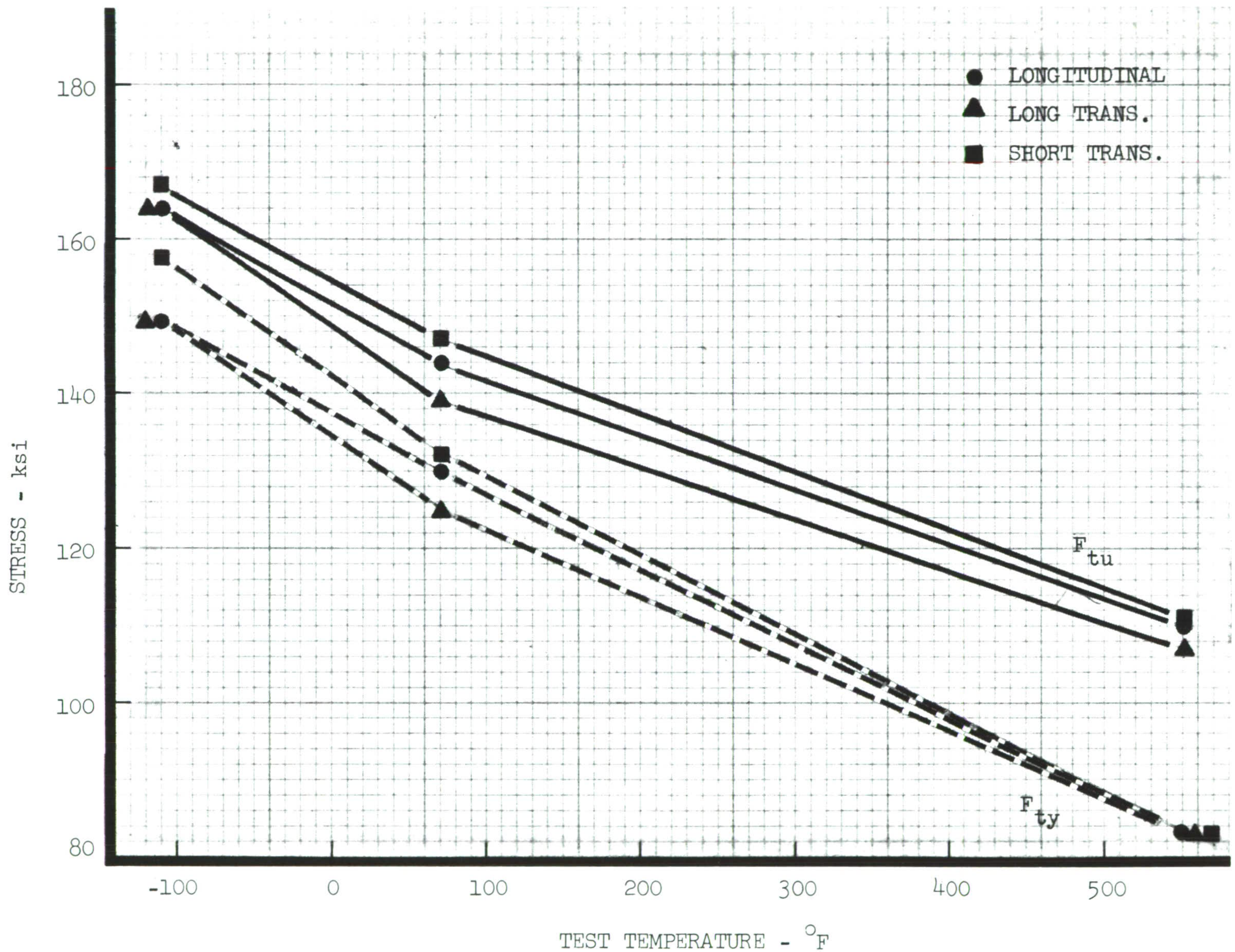


Figure 30. IMI 679 Smooth Tensile Properties Forging #1 Center Section

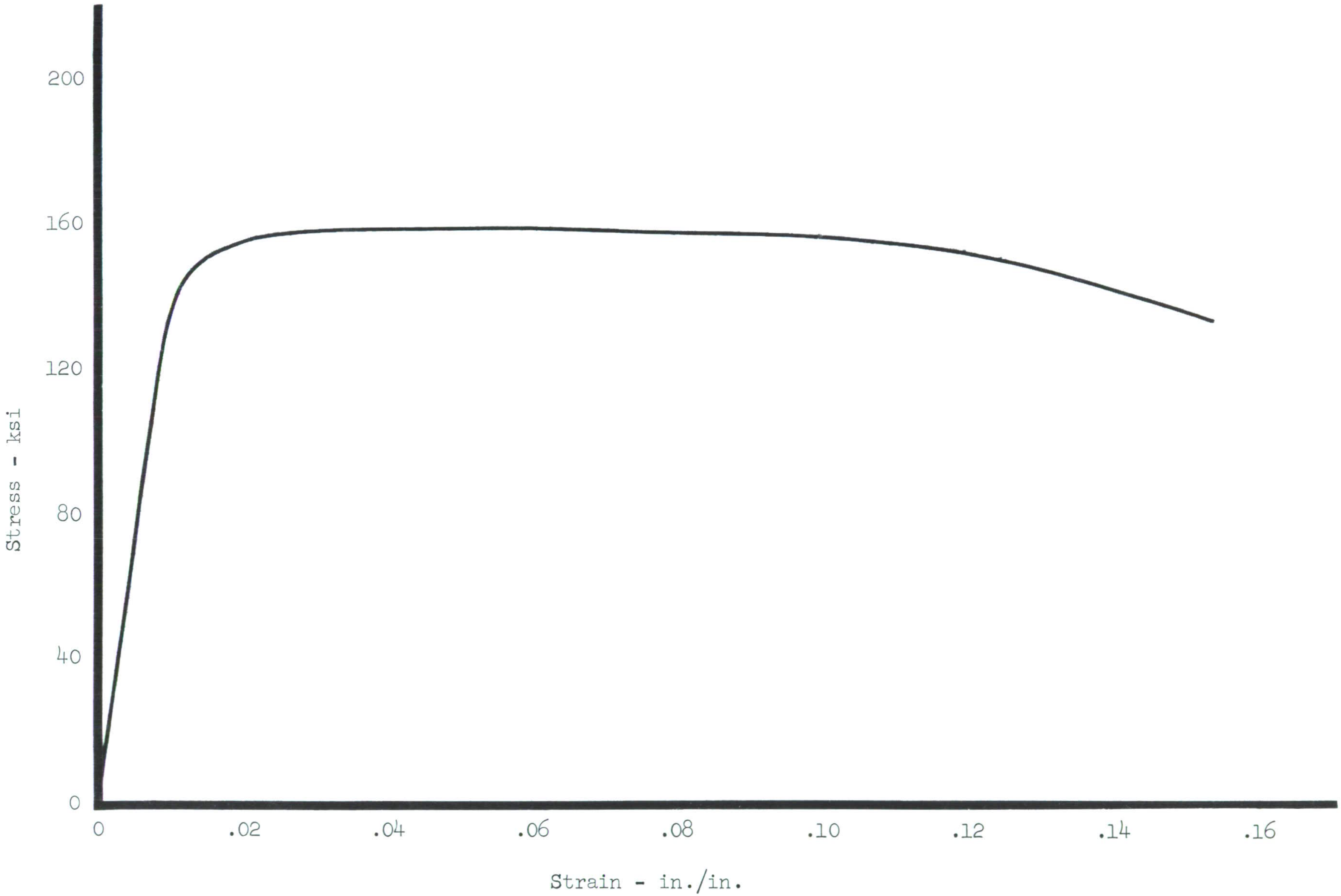


Figure 31. Ti-6Al-4V Tension Autographic Stress-Strain Curve at Room Temperature

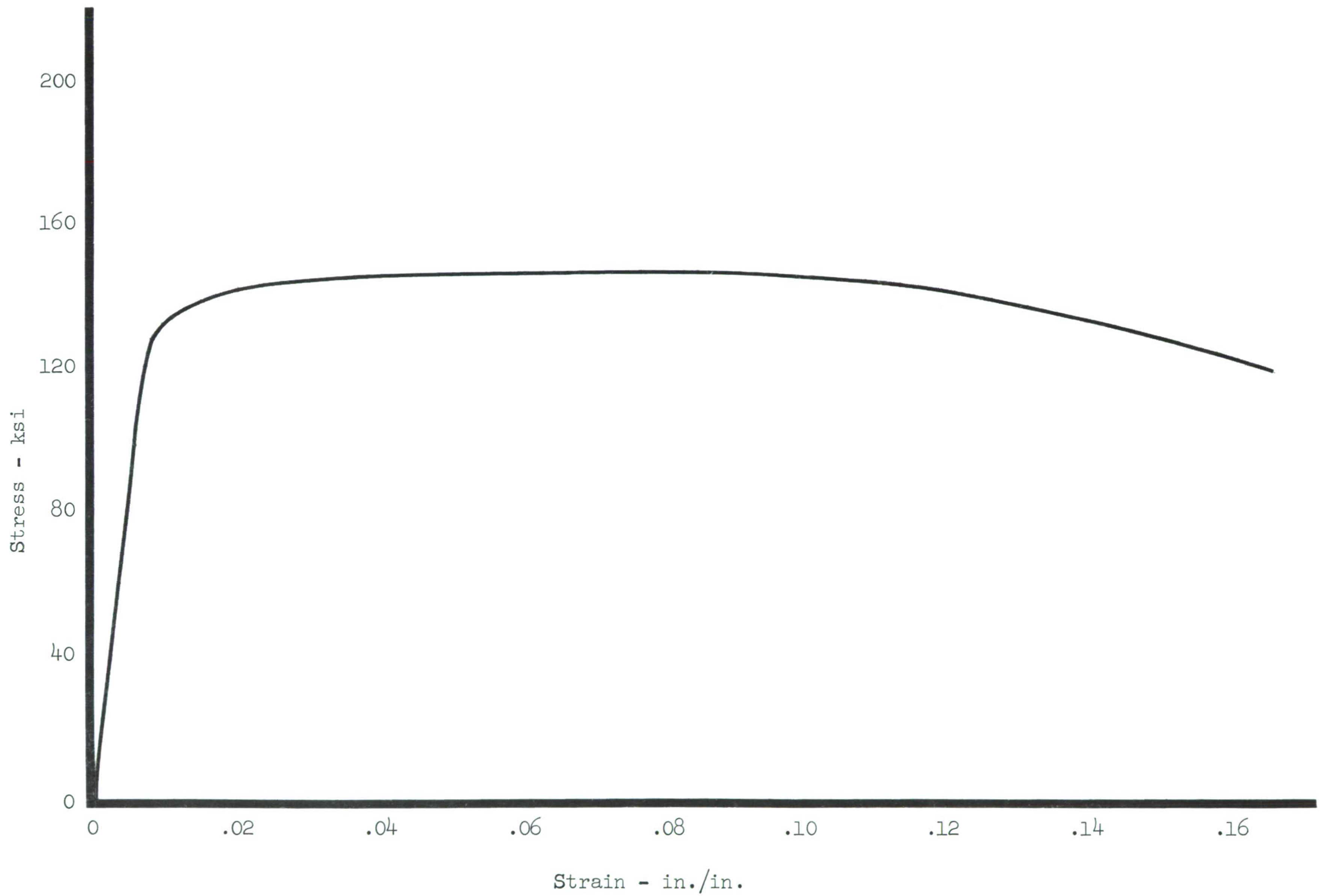


Figure 32. IMI 679 Tension Autographic Stress-Strain Curve at Room Temperature

TABLE 3 Ti-6AL-4V THICK SECTION TENSILE PROPERTIES - FORGING #1

Specimen Number	Specimen Location	Grain Dir.	Test Temp. °F.	Ultimate Tensile Strength ksi	Yield Strength 0.2% ksi	Elong. % 1 Inch	R.A. %
H40	Center	L	-110	174.0	161.0	10.0	25.0
H41				177.0	165.0	10.0	28.0
H42				176.0	-	10.0	25.0
Average				175.7	163.0	10.0	26.0
H59	Center	LT	-110	187.0	179.0	10.0	35.0
H60				176.0	169.0	9.0	29.0
H61				175.0	-	9.0	28.0
Average				179.3	174.0	9.3	30.7
HP	Edge	ST	-110	188.0	178.0	11.0	37.0
HQ				180.0	165.0	10.0	35.0
HR				179.0	163.0	11.0	35.0
Average				182.3	168.7	10.7	35.7
H31	Edge	L	RT	158.5	147.0	14.0	39.0
H38				151.5	139.1	13.0	31.0
H45				149.1	137.5	15.0	38.0
Average				153.0	141.2	14.0	36.0
H33	Center	L	RT	147.0	133.5	12.0	27.0
H34				146.2	131.7	13.0	29.0
H35				147.4	133.9	12.0	28.0
Average				146.9	133.0	12.3	28.0
H56	Center	LT	RT	165.0	157.4	10.0	25.0
H57				149.5	136.2	10.0	27.0
H58				147.6	135.3	10.0	21.0
Average				154.0	143.0	10.0	24.3

TABLE 3 Ti-6AL-4V THICK SECTION TENSILE PROPERTIES - FORGING #1
(cont'd)

Specimen Number	Specimen Location	Grain Dir.	Test Temp. °F.	Ultimate Tensile Strength ksi	Yield Strength 0.2% ksi	Elong. % 1 Inch	R.A. %
H65	Edge	ST	RT	156.4	146.1	12.0	40.0
H66				154.6	143.6	13.0	36.0
H67				165.4	152.5	11.0	27.0
Average				158.8	147.4	12.0	34.3
H68	Center	ST	RT	144.8	142.2	10.0	33.0
H69				143.3	133.1	10.0	27.0
H70				148.3	133.6	9.0	23.0
Average				145.5	136.3	9.7	27.7
H37	Edge	L	550	120.0	105.0	19.0	62.0
H44				116.0	97.4	17.0	61.0
H51				118.0	98.6	20.0	64.0
Average				118.0	100.3	18.7	62.3
H47	Center	L	550	105.0	85.3	16.0	44.0
H48				101.0	76.6	15.0	32.0
H49				102.0	78.6	18.0	42.0
Average				102.7	80.2	16.3	39.3
H62	Center	LT	550	112.0	90.9	17.0	52.0
H63				108.0	87.6	19.0	52.0
H64				101.0	80.9	17.0	46.0
Average				107.0	86.5	17.7	50.0
HS	Center	ST	550	116.3	95.3	16.0	58.0
HT				110.3	89.7	17.0	56.0
HU				111.5	86.9	19.0	59.0
Average				112.7	90.6	17.3	57.7

TABLE 3 Ti-6AL-4V THICK SECTION TENSILE PROPERTIES - FORGING #1
(cont'd)

Specimen Number	Specimen Location	Grain Dir.	Test Temp. °F.	Ultimate Tensile Strength ksi	Yield Strength 0.2% ksi	Elong. % 1 Inch	R.A. %
HV	Edge	ST	550	*Failed at Threads			
HW				110.5	87.5	18.0	54.0
HX				109.8	88.2	16.0	54.0
Average				110.1	87.8	17.0	54.0

TABLE 4 Ti-6AL-4V FLANGE TENSILE PROPERTIES - FORGING #1

Specimen Number	Specimen Location	Grain Dir.	Test Temp. °F.	Ultimate Tensile Strength ksi	Yield Strength 0.2% ksi	Elong. % 1 Inch	R.A. %
HA	Flange	L	-110	186.0	179.0	11.0	36.0
HB				176.0	168.0	11.0	37.0
HC				193.0	184.0	11.0	37.0
Average				185.0	177.0	11.0	36.7
HG	Flange	L	RT	159.8	146.6	12.0	38.2
HH				150.2	138.0	14.5	43.7
HI				163.0	150.8	11.0	31.9
Average(1)				157.7	145.1	12.5	37.9
HD	Flange	L	550	124.4	102.2	17.0	55.1
HE				115.6	94.4	19.0	58.1
HF				118.6	97.0	18.0	58.7
Average(1)				119.5	97.9	18.0	57.3
HJ	Complex Grain Flow	LT	RT	168.4	154.0	11.0	42.5
HK				152.8	138.2	13.0	37.0
HL				166.6	152.2	12.0	43.1
Average(1)				162.6	148.1	12.0	40.9
HAA	Complex Grain Flow	LT	-110	188.0	177.0	11.0	35.0
HAB				178.0	166.0	10.0	39.0
HAC				186.0	175.0	11.0	40.0
Average				184.0	172.7	10.7	38.0
HAJ	Complex Grain Flow	LT	550	116.8	95.0	16.5	56.7
HAK				107.6	86.8	19.5	54.0
HAL				117.0	95.6	15.5	56.0
Average(1)				113.8	92.5	17.2	55.6
HM	Flange	ST	RT	153.0	140.0	15.0	39.5
HN				153.6	138.4	10.5	40.8
HO				154.0	138.2	11.0	41.4
Average(1)				153.5	138.9	12.2	40.6

TABLE 4 Ti-6AL-4V FLANGE TENSILE PROPERTIES - FORGING #1
(cont'd)

Specimen Number	Specimen Location	Grain Dir.	Test Temp. °F.	Ultimate Tensile Strength ksi	Yield Strength 0.2% ksi	Elong. % 1 Inch	R.A. %
HAD	Flange	ST	550	114.5	93.3	17.0	62.0
HAE				113.0	93.7	18.0	61.0
HAF				110.3	90.4	15.0	59.0
Average				112.6	92.5	16.7	60.7
HAG	Flange	ST	550	112.6	90.6	15.5	56.7
HAH				111.4	89.2	16.0	56.7
HAI				111.6	89.4	16.0	55.6
Average(1)				111.9	89.7	15.8	56.3
HAS	Web	LT	-110	179.0	-	12.0	41.0
HAT				184.0	173.0	12.0	39.0
HAU				185.0	176.0	12.0	39.0
Average				182.7	174.5	12.0	39.7
HAM	Web	LT	RT	156.8	147.4	13.0	45.0
HAN				157.3	147.3	14.0	44.0
HAO				154.2	144.6	19.0	43.0
Average				156.1	146.4	15.3	44.0
HAP	Web	LT	550	Lost in Test			
HAQ				Lost in Test			
HAR				112.2	94.7	18.0	62.0
Average				112.2	94.7	18.0	62.0

(1) Tests conducted by the Wyman-Gordon Company

TABLE 5 Ti-6AL-4V TENSILE PROPERTIES - FORGING #2

Specimen Number	Specimen Location	Grain Dir.	Test Temp. °F.	Ultimate Tensile Strength ksi	Yield Strength 0.2% ksi	Elong. % 1 Inch	R.A. %
I13	Edge	L	RT	154.2	144.8	13.0	38.0
I16				152.4	142.8	12.0	31.0
I19				148.3	138.1	12.0	38.0
Average				151.6	141.9	12.3	35.7
I14	Mid-Radius	L	RT	144.2	132.9	12.0	33.0
I17				144.8	131.4	12.0	28.0
I20				144.4	132.4	12.0	32.0
Average				144.5	132.2	12.0	31.0
I15	Center	L	RT	151.3	138.1	12.0	29.0
I18				148.5	135.6	11.0	30.0
I21				148.3	133.0	13.0	28.0
Average				149.4	135.6	12.0	29.0
I28	Edge	LT	RT	157.0	143.8	12.0	33.0
I29				153.9	140.2	12.0	28.0
I30				160.2	147.5	12.0	26.0
Average				157.0	143.8	12.0	29.0
I25	Mid-Radius	LT	RT	146.4	134.6	10.0	32.0
I26				148.3	136.7	9.0	19.0
I27				153.8	141.6	8.0	28.0
Average				149.5	137.6	9.0	26.3
I22	Center	LT	RT	145.2	131.5	8.0	21.0
I23				144.8	132.1	8.0	22.0
I24				152.3	135.4	10.0	15.0
Average				147.4	133.0	8.7	19.3

TABLE 5 Ti-6AL-4V TENSILE PROPERTIES - FORGING #2
(cont'd)

Specimen Number	Specimen Location	Grain Dir.	Temp. °F	Ultimate Tensile Strength ksi	Yield Strength 0.2% ksi	Elong. % 1 Inch	R.A. %
I37	Edge	ST	RT	147.8	137.2	9.0	40.0
I38				145.4	134.8	10.0	32.0
I39				158.9	146.6	10.0	30.0
Average				150.7	139.5	9.7	34.0
I34	Mid-Radius	ST	RT	142.5	133.5	11.0	41.0
I35				140.6	130.8	10.0	38.0
I36				155.2	144.4	6.0	19.0
Average				146.7	136.2	9.0	32.7
I31	Center	ST	RT	142.9	131.6	9.0	28.0
I32				142.1	130.4	8.0	23.0
I33				156.3	None	9.0	24.0
Average				147.1	131.0	8.7	25.0
IC	Flange	ST	RT	148.5	138.5	15.0	47.0
ID				154.0	143.2	14.0	44.0
Average				151.3	140.9	14.5	45.5

TABLE 6 IMI 679 THICK SECTION TENSILE PROPERTIES - FORGING #1

Specimen Number	Specimen Location	Grain Dir.	Test Temp. °F.	Ultimate Tensile Strength ksi	Yield Strength 0.2% ksi	Elong. % 1 Inch	R.A. %
F40	Center	L	-110	167.0	—	13.0	39.0
F41				163.0	148.4	13.0	35.0
F42				163.0	150.7	12.0	38.0
Average				164.3	149.6	12.7	37.3
F59	Center	LT	-110	169.8	157.2	12.0	41.0
F60				162.9	146.8	14.0	43.0
F61				160.2	144.4	13.0	43.0
Average				164.3	149.5	13.0	42.3
FP	Edge	ST	-110	169.4	160.7	13.0	43.0
FQ				162.9	150.1	11.0	42.0
FR				169.8	162.1	12.0	42.0
Average				167.4	157.6	12.0	42.3
F31	Edge	L	RT	146.0	134.0	16.0	44.0
F38				145.6	132.0	15.0	42.0
F45				147.8	133.5	13.0	33.0
Average				146.5	133.2	14.7	39.7
F33	Center	L	RT	142.0	128.0	16.0	41.0
F34				140.8	126.7	15.0	40.0
F35				143.1	129.2	16.0	40.0
Average				142.0	128.0	15.7	40.3
F56	Center	LT	RT	143.0	129.0	20.0	43.0
F57				139.0	125.0	16.0	45.0
F58				135.5	120.5	15.0	44.0
Average				139.2	124.8	17.0	44.0

TABLE 6 IMI 679 THICK SECTION TENSILE PROPERTIES - FORGING #1
(cont'd)

Specimen Number	Specimen Location	Grain Dir.	Test Temp. °F.	Ultimate Tensile Strength ksi	Yield Strength 0.2% ksi	Elong. % 1 Inch	R.A. %
F65	Edge	ST	RT	149.8	135.9	14.0	41.0
F66				151.1	136.2	16.0	40.0
F67				148.5	133.9	15.0	43.0
Average				149.8	135.3	15.0	41.3
F68	Center	ST	RT	144.0	129.0	14.0	35.0
F69				145.0	130.0	15.0	37.0
F70				143.7	129.0	13.0	41.0
Average				144.2	129.3	14.0	37.7
F37	Edge	L	550	108.6	83.3	17.0	47.0
F44				116.9	92.0	17.0	41.0
F51				118.1	89.8	16.0	42.0
Average				114.5	88.4	16.7	43.3
F47	Center	L	550	103.5	79.0	19.0	54.0
F48				105.3	76.9	19.0	53.0
F49				106.8	80.2	18.0	50.0
Average				105.2	78.7	18.7	52.3
F62	Center	LT	550	111.2	87.2	18.0	51.0
F63				106.5	80.8	17.0	47.0
F64				105.2	81.4	20.0	50.0
Average				107.6	83.1	18.3	49.3
FS	Center	ST	550	112.9	84.6	17.0	49.0
FT				113.3	86.0	19.0	50.0
FU				108.4	81.1	17.0	51.0
Average				111.5	83.9	17.7	50.0

TABLE 6 IMI 679 THICK SECTION TENSILE PROPERTIES - FORGING #1
(cont'd)

Specimen Number	Specimen Location	Grain Dir.	Test Temp. °F.	Ultimate Tensile Strength ksi	Yield Strength 0.2% ksi	Elong. % 1 Inch	R.A. %
FV	Edge	ST	550	112.4	84.3	18.0	49.0
FW				113.3	81.9	19.0	50.0
FX				110.6	82.8	18.0	50.0
Average				112.1	83.0	18.3	49.7

TABLE 7 IMI 679 FLANGE TENSILE PROPERTIES - FORGING #1

Specimen Number	Specimen Location	Grain Dir.	Test Temp. °F.	Ultimate Tensile Strength ksi	Yield Strength 0.2% ksi	Elong. % 1 Inch	R.A. %
FA	Flange	L	-110	175.0	164.0	12.0	39.0
FB				166.0	153.0	13.0	43.0
FC				168.0	163.0	12.0	40.0
Average				169.7	160.0	12.3	40.7
FG	Flange	L	RT	150.8	133.0	15.0	43.7
FH				144.0	127.6	16.0	45.5
FI				147.0	130.2	14.5	45.0
Average(1)				147.3	130.3	15.2	44.7
FD	Flange	L	550	120.6	93.0	17.0	43.7
FE				111.4	87.2	18.0	56.0
FF				118.4	89.8	19.0	50.0
Average(1)				116.8	90.0	18.0	49.9
FJ	Complex Grain Flow	LT	RT	150.0	133.0	15.5	41.7
FK				141.6	126.0	16.0	47.8
FL				149.6	132.2	14.5	42.5
Average(1)				147.1	130.4	15.3	44.0
FAA	Complex Grain Flow	LT	-110	164.4	150.9	13.0	41.0
FAB				162.1	148.7	13.0	42.0
FAC				167.0	154.6	13.0	42.0
Average				164.5	151.4	13.0	41.7
FAJ	Complex Grain Flow	LT	550	115.2	89.2	17.0	46.7
FAK				110.6	85.8	19.0	53.4
FAL				114.0	88.0	15.5	49.0
Average(1)				113.3	87.7	17.2	49.7
FM	Flange	ST	RT	147.6	131.8	12.0	44.4
FN				146.0	130.0	13.0	45.0
FO				146.0	130.4	10.5	31.9
Average(1)				146.5	130.7	11.8	40.4

TABLE 7 IMI 679 FLANGE TENSILE PROPERTIES - FORGING #1
(cont'd)

Specimen Number	Specimen Location	Grain Dir.	Test Temp. °F.	Ultimate Tensile Strength ksi	Yield Strength 0.2% ksi	Elong. % 1 Inch	R.A. %
FAD	Flange	ST	550	113.0	86.4	16.0	48.0
FAE				Lost in Test			
FAF				115.0	89.4	16.0	49.0
Average				114.0	87.9	16.0	48.5
FAG	Flange	ST	550	114.0	88.0	15.5	50.0
FAH				114.0	87.2	16.0	50.0
FAI				115.0	88.8	16.5	49.0
Average(1)				114.3	88.0	16.0	49.7
FAS	Web	LT	-110	170.0	156.0	14.0	42.0
FAT				170.0	162.0	12.0	36.0
FAU				171.0	160.0	13.0	43.0
Average				170.3	159.3	13.0	40.3
FAM	Web	LT	RT	145.0	132.0	15.0	50.0
FAN				146.0	133.0	17.0	49.0
FAO				146.0	138.0	17.0	46.0
Average				145.7	134.3	16.3	48.3
FAP	Web	LT	550	113.0	89.2	18.0	50.0
FAQ				114.0	87.2	18.0	53.0
FAR				115.0	90.1	18.0	53.0
Average				114.0	88.8	18.0	52.0

(1) Tests conducted by the Wyman-Gordon Company

TABLE 8 IMI 679 TENSILE PROPERTIES - FORGING #2

Specimen Number	Specimen Location	Grain Dir.	Test Temp. °F	Ultimate Tensile Strength ksi	Yield Strength 0.2% ksi	Elong. % 1 Inch	R.A. %
G13	Edge	L	RT	149.9	134.8	13.0	34.0
G16				148.9	133.6	14.0	35.0
G19				150.2	135.0	13.0	32.0
Average				149.7	134.5	13.3	33.7
G14	Mid-Radius	L	RT	143.0	129.1	16.0	33.0
G17				145.3	130.4	14.0	36.0
G20				146.1	131.5	14.0	36.0
Average				144.8	130.3	14.7	35.0
G15	Center	L	RT	148.6	133.6	14.0	31.0
G18				140.2	125.9	14.0	36.0
G21				141.0	126.9	14.0	38.0
Average				143.3	128.8	14.0	35.0
G28	Edge	LT	RT	147.8	134.9	13.0	40.0
G29				146.6	133.5	14.0	42.0
G30				146.5	133.1	14.0	39.0
Average				147.0	133.8	13.7	40.3
G25	Mid-Radius	LT	RT	142.2	127.6	14.0	43.0
G26				142.6	127.1	15.0	37.0
G27				142.8	128.5	12.0	41.0
Average				142.5	127.7	13.3	40.3
G22	Center	LT	RT	139.5	124.2	14.0	43.0
G23				139.4	124.6	14.0	43.0
G24				140.0	125.2	14.0	41.0
Average				139.6	124.7	14.0	42.3

TABLE 8 IMI 679 TENSILE PROPERTIES - FORGING #2
(cont'd)

Specimen Number	Specimen Location	Grain Dir.	Test Temp. °F.	Ultimate Tensile Strength ksi	Yield Strength 0.2% ksi	Elong. % 1 Inch	R.A. %
G37	Edge	ST	RT	147.9	133.6	14.0	41.0
G38				149.9	134.6	13.0	38.0
G39				146.8	133.3	15.0	41.0
Average				148.2	133.8	14.0	40.0
G34	Mid-Radius	ST	RT	143.6	129.0	14.0	39.0
G35				144.0	129.7	15.0	42.0
G36				145.2	130.7	15.0	42.0
Average				144.3	129.8	14.7	41.0
G31	Center	ST	RT	137.3	121.2	11.0	30.0
G32				138.0	123.2	14.0	42.0
G33				140.0	126.7	14.0	43.0
Average				138.4	123.7	13.0	38.3
GC	Flange	ST	RT	149.7	134.6	16.0	41.0
GD				149.5	136.1	16.0	41.0
Average				149.6	135.3	16.0	41.0

NOTCHED TENSILE PROPERTIES

Notched tension tests were conducted on specimens taken from the light section flange areas as well as at edge, mid-radius and center locations of the forging heavy center section in the Ti-6Al-4V and IMI 679. The notch tensile data are presented in Tables 9 and 10. Figure 33 presents a plot of notched to un-notched tensile strength ratios for various specimen locations in the Ti-6Al-4V and IMI 679 forgings. Room temperature NTS/UTS ratios of 1.35 and higher were obtained in Ti-6Al-4V and IMI 679 in all grain directions and at all locations. Whereas, NTS/UTS ratios over 1.2 for Ti-6Al-6V-2Sn and under 1.0 for Ti-13V-11Cr-3Al were obtained in tests previously conducted (Ref. 1). All test specimens were taken from identical locations in each of the four alloys.

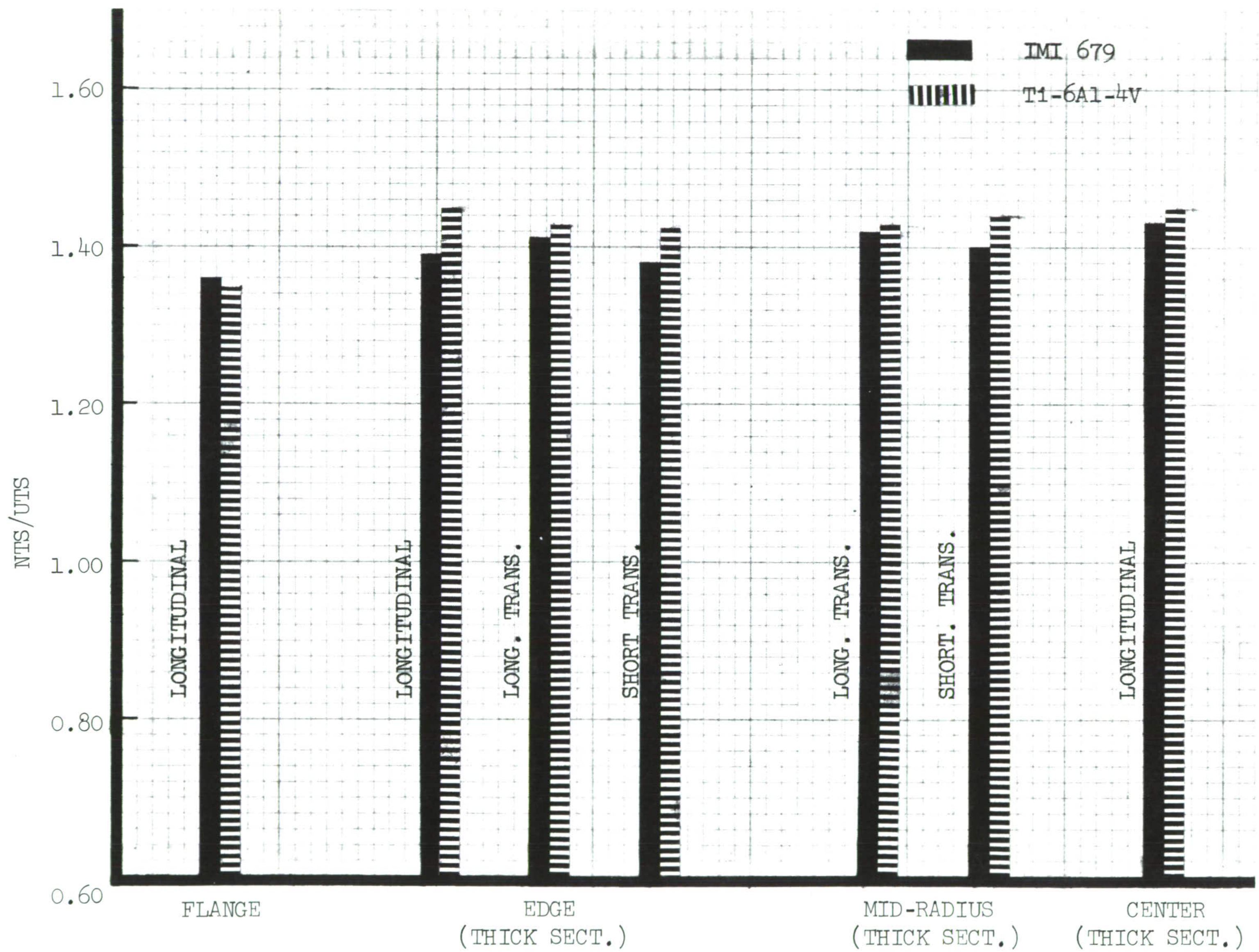


Figure 33. Comparison of Room Temperature Notched Tensile Properties (K_T = 3.9)

TABLE 9 Ti-6AL-4V NOTCHED TENSILE PROPERTIES

Forging Number	Specimen Number	Specimen Location	Grain Dir.	Test Temp. °F.	Notched Tensile Strength ksi	NTS/UTS (K_t = 3.9)
#1	H43	Mid-radius	L	-110	239.0	
	H50				243.0	
	Average				241.0	1.38
	H39	Mid-radius	L	RT	211.4	
	H46				216.5	
	Average				213.9	1.39
#2	I42	Edge	L	RT	218.1	
	I43				222.8	
	Average				220.5	1.45
	I40	Center	L	RT	214.0	
	I41				218.9	
	Average				216.5	1.45
	I44	Edge	LT	RT	225.5	
	I45				225.5	
	Average				225.5	1.43
	I46	Mid-radius	LT	RT	216.5	
	I47				211.4	
	Average				214.0	1.43
	I48	Edge	ST	RT	220.6	
	I49				221.7	
	Average				221.2	1.46
	I50	Mid-radius	ST	RT	220.3	
	I51				209.8	
	Average				215.1	1.44
	IA	Flange	L	RT	213.2	
	IB				213.0	
	Average				213.1	1.35

TABLE 10 IMI 679 NOTCHED TENSILE PROPERTIES

Forging Number	Specimen Number	Specimen Location	Grain Dir.	Test Temp. °F	Notched Tensile Strength ksi	NTS/UTS (K_t = 3.9)
#1	F43	Mid-radius	L	-110	230.0	
	F50				232.0	
	Average				231.0	1.41
	F39	Mid-radius	L	RT	207.4	
	F46				206.6	
	Average				207.0	1.42
#2	G42	Edge	L	RT	210.0	
	G43				206.0	
	Average				208.0	1.39
	G40	Center	L	RT	206.0	
	G41				204.0	
	Average				205.0	1.43
	G44	Edge	LT	RT	208.0	
	G45				206.0	
	Average				207.0	1.41
	G46	Mid-radius	LT	RT	205.0	
	G47				201.0	
	Average				203.0	1.42
	G48	Edge	ST	RT	204.0	
	G49				204.0	
	Average				204.0	1.38
	G50	Mid-radius	ST	RT	202.0	
	G51				200.0	
	Average				201.0	1.40
	GA	Flange	L	RT	196.0	
	GB				207.0	
	Average				201.5	1.36

COMPRESSION PROPERTIES

Compression properties for Ti-6Al-4V and IMI 679 are given in Tables 11 and 12. The effect of temperature on compression yield strength in Ti-6Al-4V is shown in Figure 34. Similar data on IMI 679 are presented in Figure 35. Typical autographic compression stress-strain curves for both alloys at room temperature and 550°F are shown in Figures 36 and 37 respectively. Compression properties were found to be quite uniform; the variation in values due to location and grain direction was small.

At room temperature and -110°F, the compression properties of Ti-6Al-4V and IMI 679 were in the same range as the ultimate tensile strengths of each alloy. However, the compression properties dropped off more rapidly than the ultimate tensile strength at 550°F.

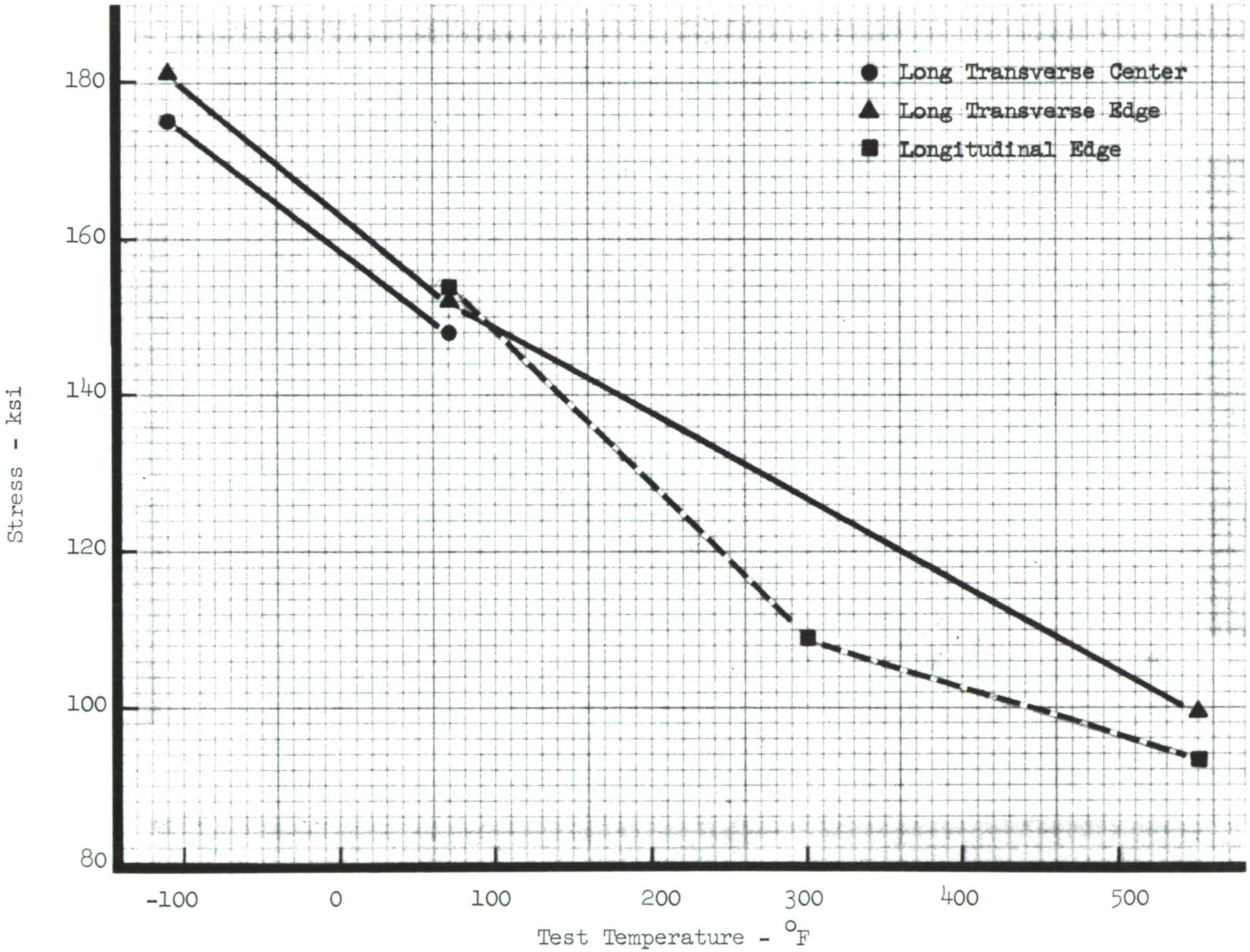


Figure 34. Ti-6Al-4V Effect of Temperature on Compression Yield

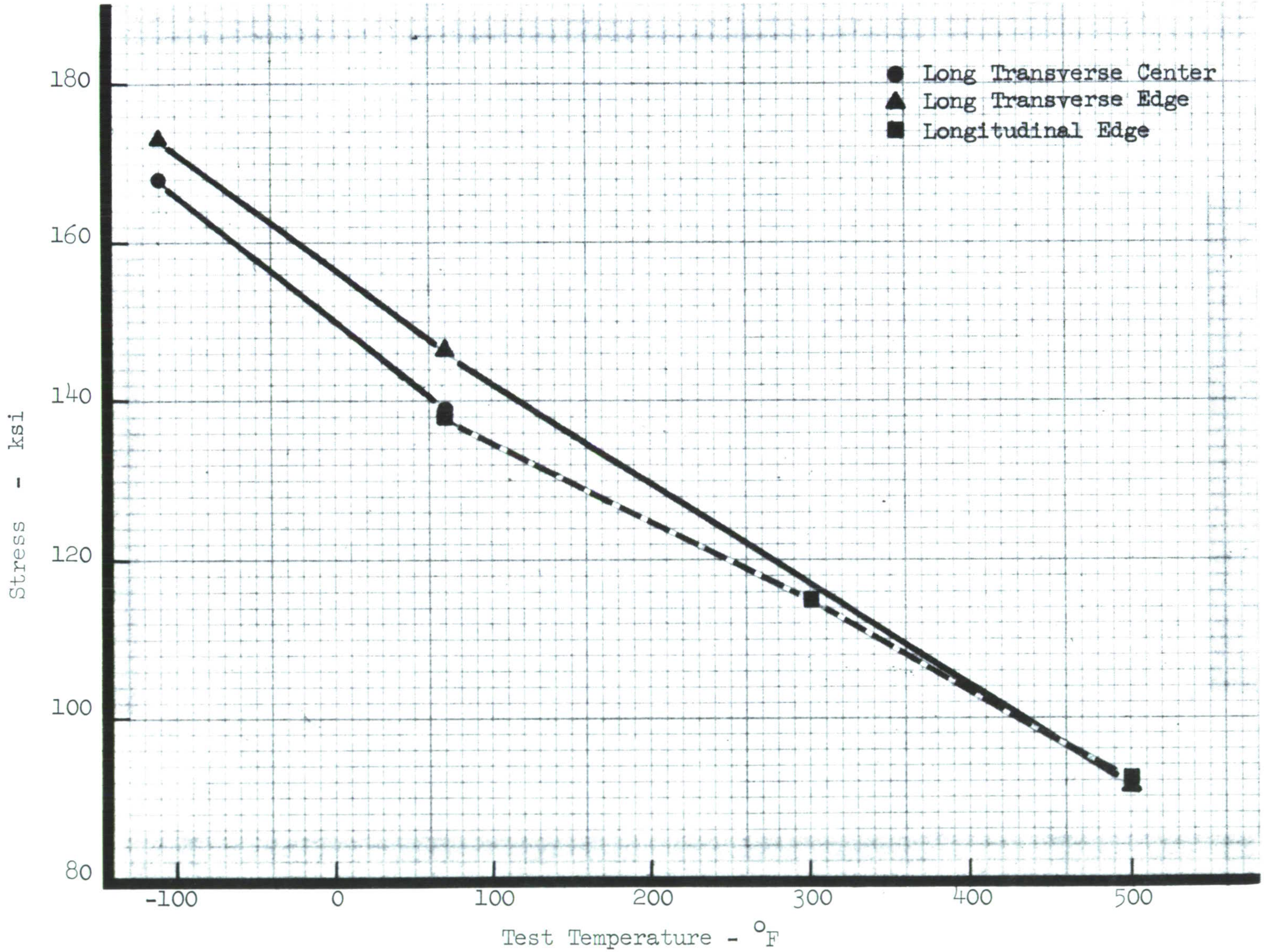


Figure 35. IMI 679 Effect of Temperature on Compression Yield

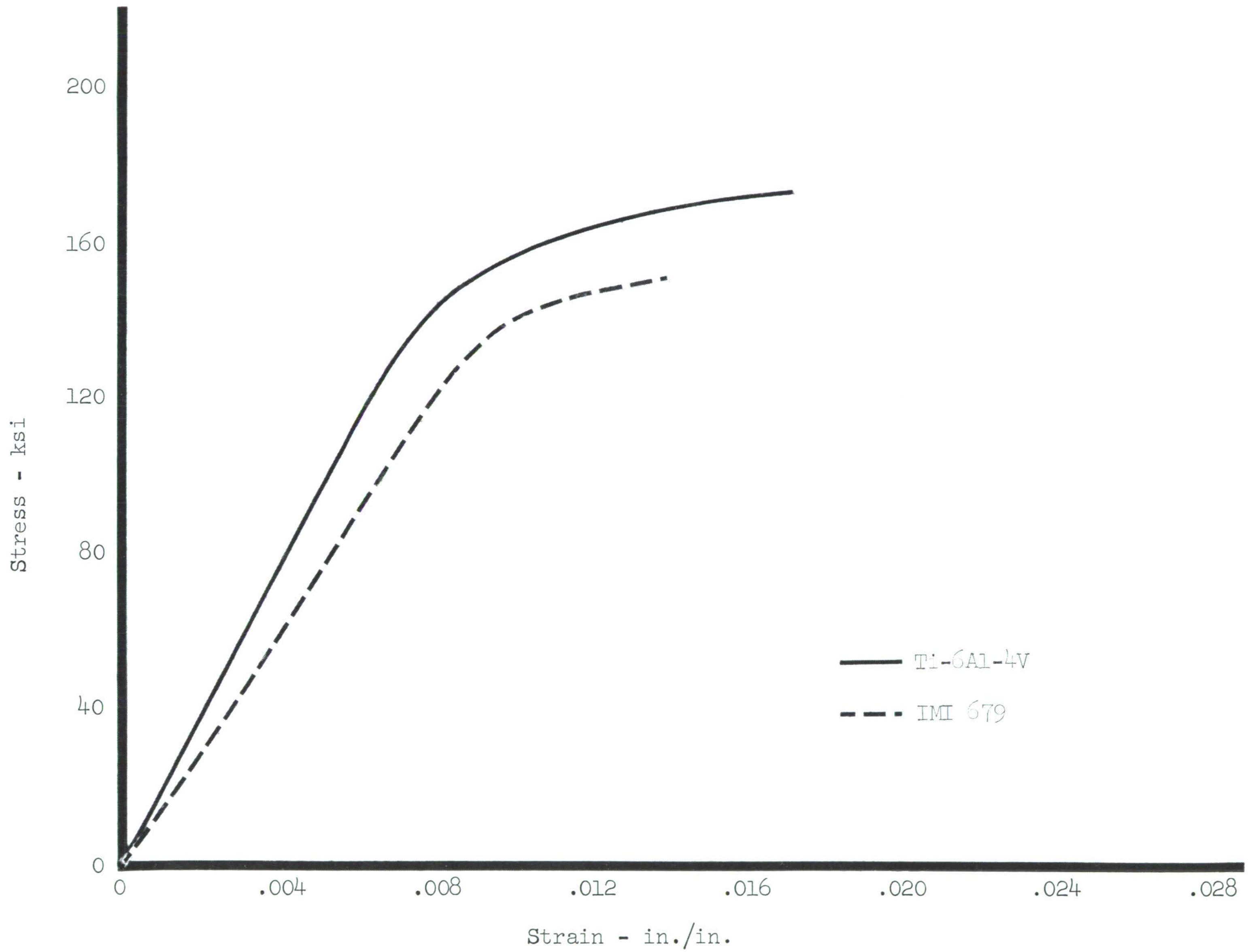


Figure 36. Ti-6Al-4V and IMI 679 Compression Autographic Stress-Strain Curves at Room Temperature

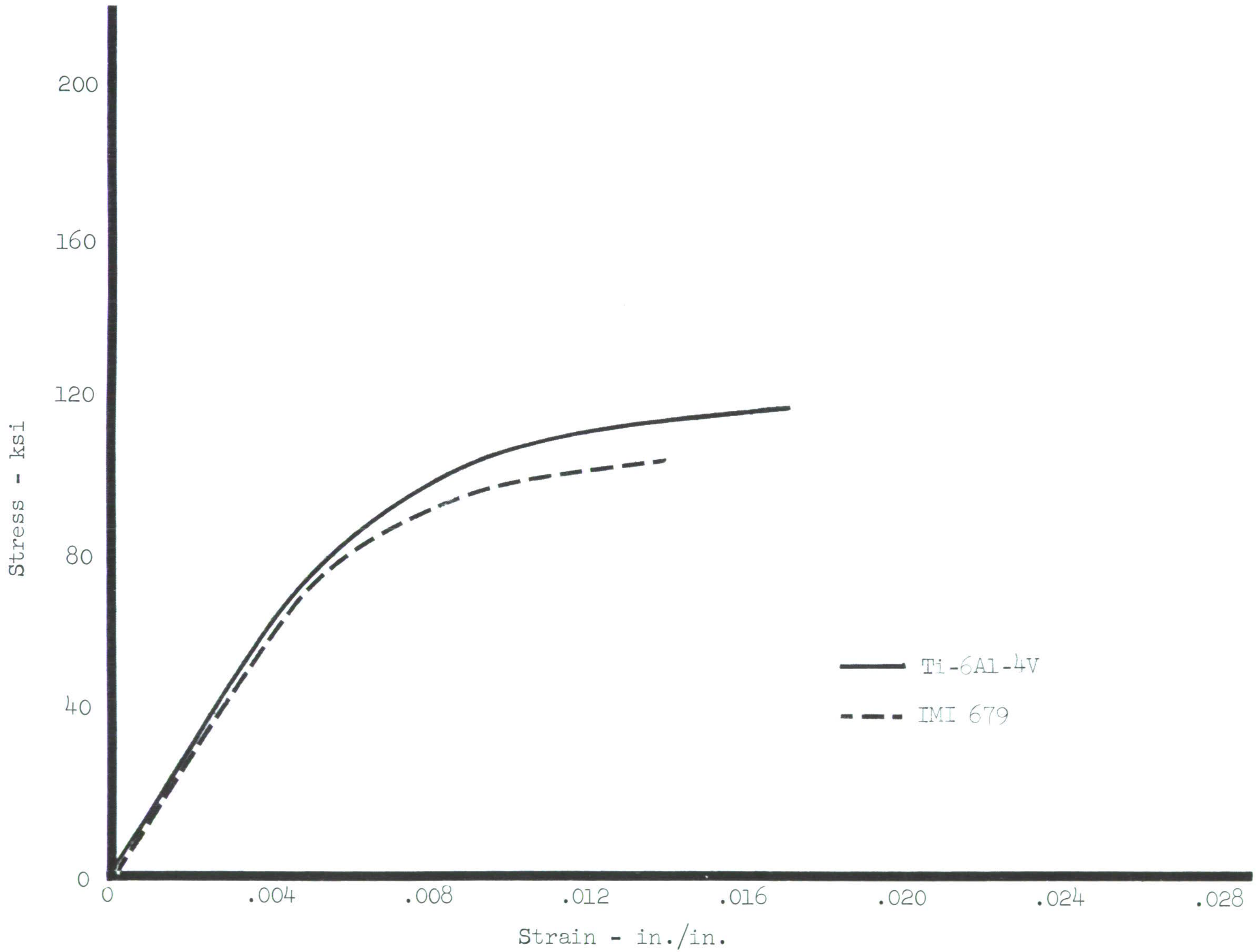


Figure 37. Ti-6Al-4V and IMI679 Compression Autographic Stress-Strain Curves at 550°F

TABLE 11 Ti-6AL-4V THICK SECTION COMPRESSION PROPERTIES

Forging Number	Specimen Number	Specimen Location	Grain Dir.	Test Temp. °F.	Compression Yield Strength ksi
#2	I11	Edge	LT	-110	182.9
	I12				179.8
	Average				181.4
	I9	Center	LT	-110	173.4
	I10				175.8
	Average				174.6
	I5	Edge	LT	RT	147.5
	I6				150.3
	Average				148.9
	I7	Center	LT	RT	149.2
	I8				146.9
	Average				148.1
#1	H23	Edge	L	RT	154.1
	H24				153.1
	Average				153.6
	H27	Edge	LT	RT	158.4
	H28				152.1
	Average				155.3
#3	HC1	Edge	L	300	111.0
	HC2				107.0
	Average				109.5

TABLE 11 Ti-6AL-4V THICK SECTION COMPRESSION PROPERTIES (cont'd)

Forging Number	Specimen Number	Specimen Location	Grain Dir.	Test Temp. °F.	Compression Yield Strength ksi
#1	H25	Edge	L	550	93.8
	H26				93.0
	Average				93.4
	H29	Edge	LT	550	100.7
	H30				98.9
	Average				99.8

TABLE 12 IMI 679 THICK SECTION COMPRESSION PROPERTIES

Forging Number	Specimen Number	Specimen Location	Grain Dir.	Test Temp. °F	Compression Yield Strength ksi
#2	G11	Edge	LT	-110	175.5
	G12				170.7
	Average				173.1
	G9	Center	LT	-110	169.2
	G10				166.8
	Average				168.0
	G5	Edge	LT	RT	148.7
	G6				148.0
	Average				148.4
	G7	Center	LT	RT	138.1
	G8				141.5
	Average				139.8
#1	F23	Edge	L	RT	135.8
	F24				140.8
	Average				138.3
	F27	Edge	LT	RT	144.1
	F28				144.9
	Average				144.5
#3	FC1	Edge	L	300	112.0
	FC2				117.0
	Average				115.0

TABLE 12 IMI 679 THICK SECTION COMPRESSION PROPERTIES (cont'd)

Forging Number	Specimen Number	Specimen Location	Grain Dir.	Test Temp. °F.	Compression Yield Strength ksi
#1	F25	Edge	L	550	90.6
	F26				93.9
	Average				92.3
	F29	Edge	LT	550	92.4
	F30				90.7
	Average				91.6

SHEAR AND BEARING PROPERTIES

Results of room temperature and 550°F double shear testing Ti-6Al-4V and IMI 679 material are given in Table 13. The specimens were taken in the longitudinal grain direction from the thick section of the forgings. The values obtained on the Ti-6Al-4V forgings were in good agreement with published values. Shear values on IMI 679 from other sources were not available for comparison.

Bearing ultimate and yield strength values at room temperature and 550°F for Ti-6Al-4V and IMI 679 are given in Table 14.

TABLE 13 DOUBLE SHEAR PROPERTIES OF Ti-6Al-4V and IMI 679

Material	Forging Number	Specimen Number	Grain Direction	Test Temperature °F	Ultimate Shear Ksi
Ti-6Al-4V	#1	H71	L	RT	107.3
		H72	L	RT	97.2
		Average			102.3
		H73	L	550	79.6
		H74	L	550	73.8
		Average			76.7
IMI 679	#1	F71	L	RT	101.8
		F72	L	RT	99.9
		Average			100.9
		F73	L	550	70.6
		F74	L	550	71.8
		Average			71.2

TABLE 14 BEARING TEST RESULTS

Material	Forging Number	Specimen Number	Grain Dir.	Test Temp. °F	F_{bru}^{*} ksi	F_{bry} ksi
Ti-6Al-4V	#1	HY	L	RT	313.8	242.1
		HZ			320.0	245.0
		Average			316.9	243.6
	#2	HY1	L	550	258.3	178.2
		HZ1			262.6	197.5
		Average			260.5	187.9
IMI 679	#1	FY	L	RT	305.6	233.9
		FZ			305.9	228.8
		Average			305.8	231.4
	#2	FY1	L	550	222.9	176.1
		FZ1			239.1	177.2
		Average			231.0	176.7

*Thickness = 1/16", Bearing hole diameter = 0.250";(e/d = 2.0)

FRACTURE TOUGHNESS

Pre-cracked round bar specimens were tested to determine the fracture toughness characteristics (K_{1c}) in the Ti-6Al-4V and IMI 679 forgings. All specimens were taken in the short transverse grain direction so they could be readily compared to the data on Ti-13V-11Cr-3Al and Ti-6Al-6V-2Sn (Ref. 1). Fracture toughness results on Ti-6Al-4V and IMI 679 are presented in Tables 15 and 16 and shown graphically in Figure 38.

Forging No. 1 of Ti-6Al-4V had the highest room temperature fracture toughness values of the two alloys tested in this program. Values of K_{Ic} from similar locations in forging No. 1 and forging No. 2 of each alloy were compared. The values obtained showed very good agreement for both the Ti-6Al-4V and IMI 679. A slight decrease in K_{1c} values was noted in both the Ti-6Al-4V and IMI 679 at a test temperature of -110°F.

Two machined specimens of each alloy were exposed to 550°F for 1000 hours in an unstressed condition. After exposure the specimens were fatigue cracked and tested at room temperature. The thermal exposure treatment had no significant effect on the fracture toughness properties in either the Ti-6Al-4V or IMI 679. See Tables 15 and 16.

Data obtained in Reference (1) indicated that the room temperature K_{1c} values for Ti-6Al-6V-2Sn are comparable to those obtained for Ti-6Al-4V. It should be noted, however, that the Ti-6Al-6V-2Sn was at an ultimate tensile strength level of approximately 160 ksi.

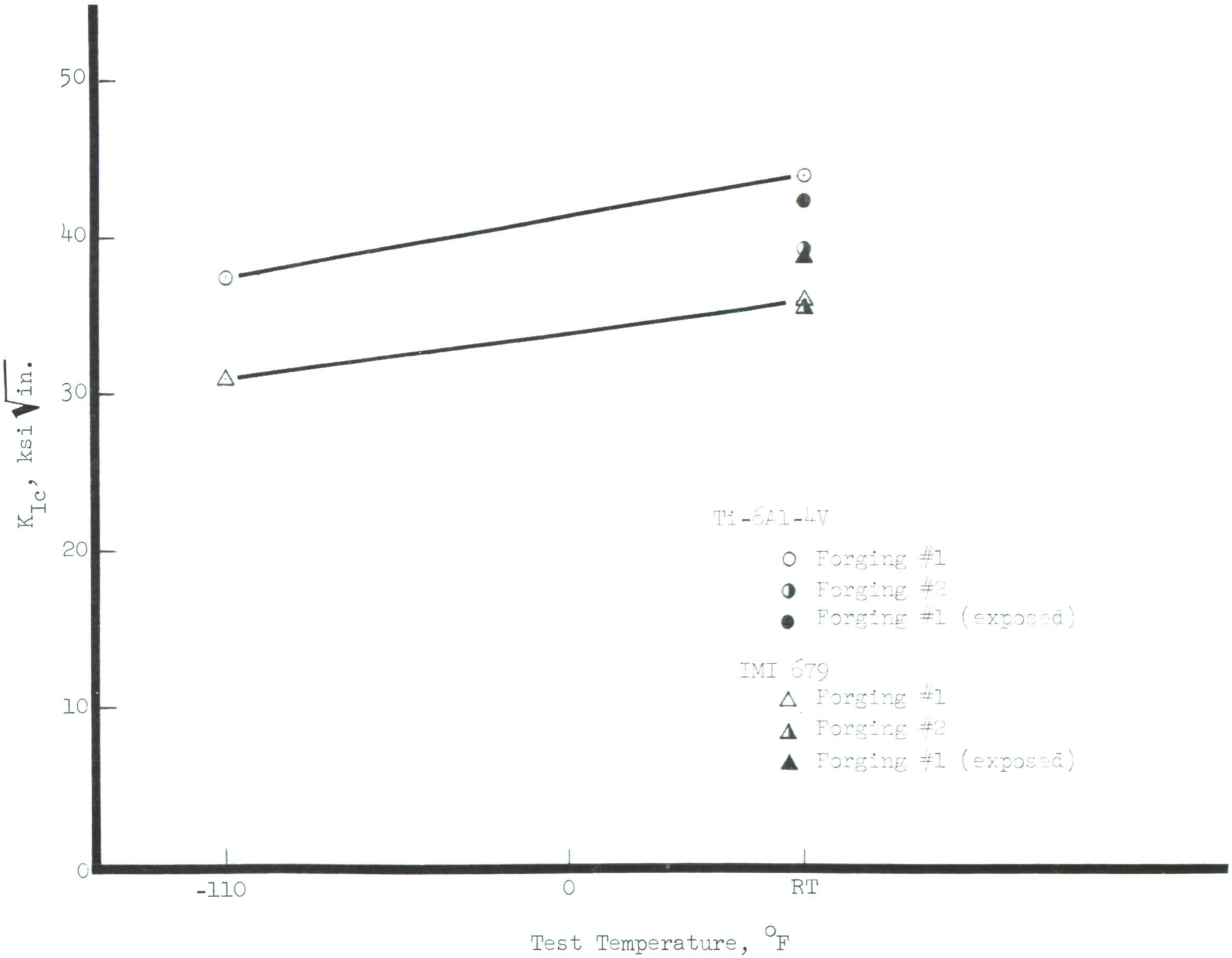


Figure 38. Comparison of Short Transverse Fracture Toughness Properties

TABLE 15 FRACTURE TOUGHNESS PROPERTIES IN Ti-6Al-4V

Forging Number	Specimen Number	Test Temp. °F	Major Diameter (D) Inches	Net Diameter (d) Inches	Maximum Load (P) 10^3 lbs	σ_{Net} ksi	Yield Strength 0.2% ksi	$\frac{\sigma_{Net}}{\sigma_{ys}}$	K_{1c} ksi $\sqrt{in.}$
#1	H 5	-110	0.751	0.420	15.3	110	169	0.65	39
	H 6	-110	0.753	0.380	11.8	104	169	0.62	36
	H 2 (1)	RT							
	H 1	RT	0.750	0.550	29.8	125	147	0.85	44
	H 8 (1)	RT							
	H 3 (2)	RT	0.750	0.570	31.8	125	147	0.85	44
	H 4 (2)	RT	0.750	0.470	19.6	113	136	0.83	41
#2	I 1 (1)	RT							
	I 2	RT	0.750	0.360	11.6	114	131	0.87	38
	I 3	RT	0.751	0.390	13.7	115	140	0.82	40
	I 4	RT	0.753	0.385	13.5	116	131	0.89	40

(1) Fatigue crack too deep and eccentric to yield valid data
(2) Exposed 1000 hours at 550°F prior to test

~~40.25~~ 41.2

TABLE 16 FRACTURE TOUGHNESS PROPERTIES IN IMI 679

Forging Number	Specimen Number	Test Temp. °F	Major Diameter (D) Inches	Net Diameter (d) Inches	Maximum Load (P) 10^3 lbs	σ_{Net} ksi	Yield Strength 0.2% ksi	$\frac{\sigma_{Net}}{\sigma_{ys}}$	K_{1c} ksi $\sqrt{in.}$
#1	F 5	-110	0.751	0.370	9.5	88	158	0.56	30
	F 6	-110	0.750	0.390	11.1	93	158	0.59	32
	F 2	RT	0.750	0.370	11.1	103	129	0.80	34
	F 1	RT	0.750	0.420	14.2	103	135	0.76	36
	F 8	RT	0.751	0.420	14.7	106	129	0.82	38
	F 3 (1)	RT	0.750	0.490	20.2	107	135	0.79	39
	F 4 (1)	RT	0.751	0.500	21.4	109	129	0.85	39
#2	G 1	RT	0.750	0.410	12.8	97	134	0.72	34
	G 2	RT	0.749	0.410	14.4	109	124	0.88	38
	G 3	RT	0.749	0.415	14.0	104	134	0.78	36
	G 4	RT	0.750	0.395	12.3	100	124	0.81	35

(1) Exposed 1000 hours at 550°F prior to test

~~35.55~~
36.5

FATIGUE PROPERTIES

Smooth and notched axial tension fatigue tests were conducted on Ti-6Al-4V and IMI 679. A stress of R=0.1 was used in all testing. The test results are presented in Tables 17 through 20 and shown graphically in Figures 39 through 42. In general, the longitundinal room temperature smooth and notched properties of IMI 679 are superior to those exhibited by Ti-6Al-4V. However, smooth fatigue properties at 550°F were comparable in the Ti-6Al-4V and IMI 679.

Short transverse smooth fatigue tests were conducted at room temperature on Ti-6Al-4V and IMI 679 and compared to the longitudinal tests. No difference in fatigue properties was noted in either alloy due to grain direction. Longitudinal smooth fatigue tests were conducted on the alloy billets. Fatigue properties in both the Ti-6Al-4V and IMI 679 billets were found to be lower than those in the forging.

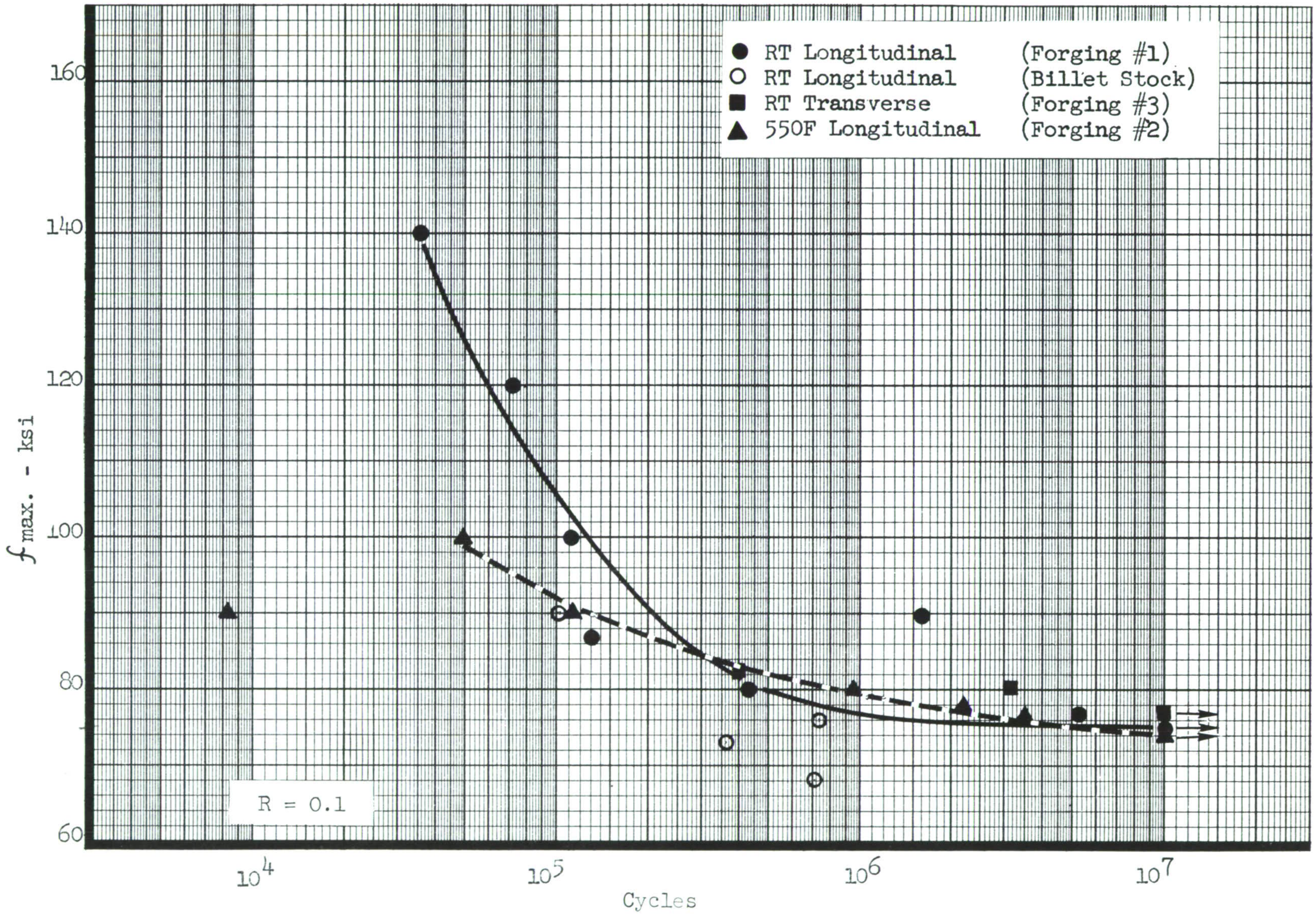


Figure 39. Ti-6Al-4V Smooth Fatigue Properties

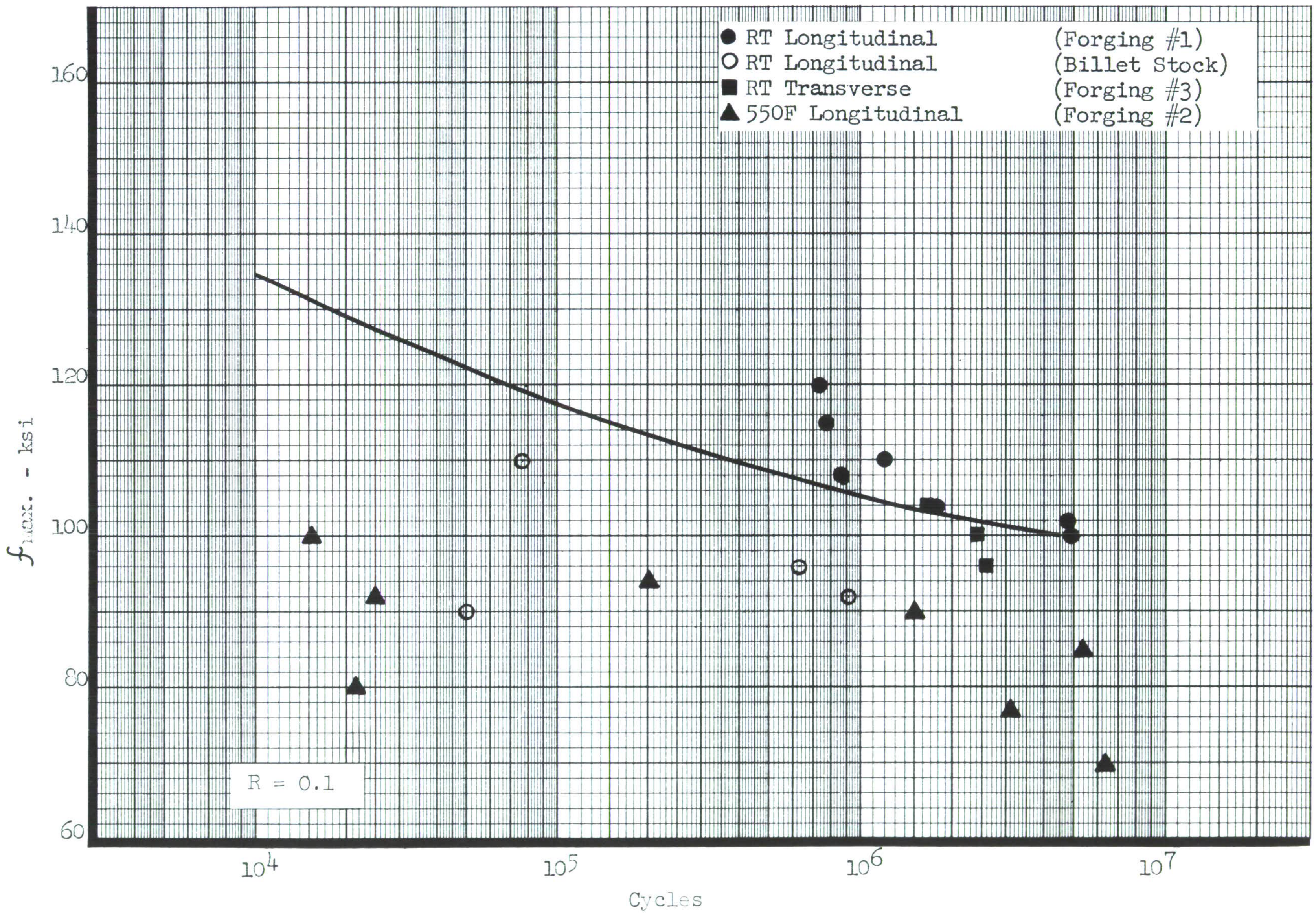


Figure 40. IMI 679 Smooth Fatigue Properties

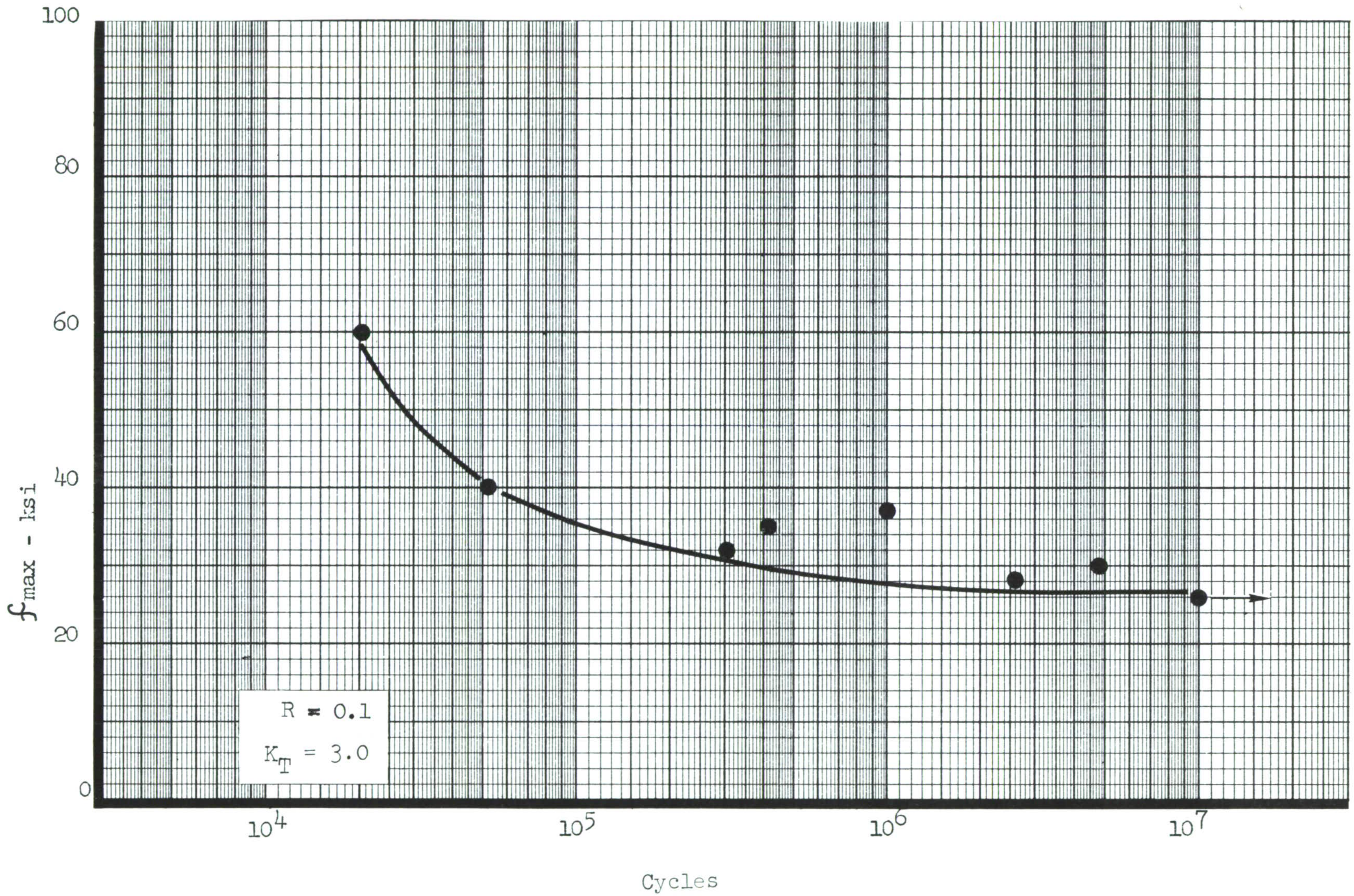


Figure 41. Ti-6Al-4V Room Temperature Notched Fatigue Properties

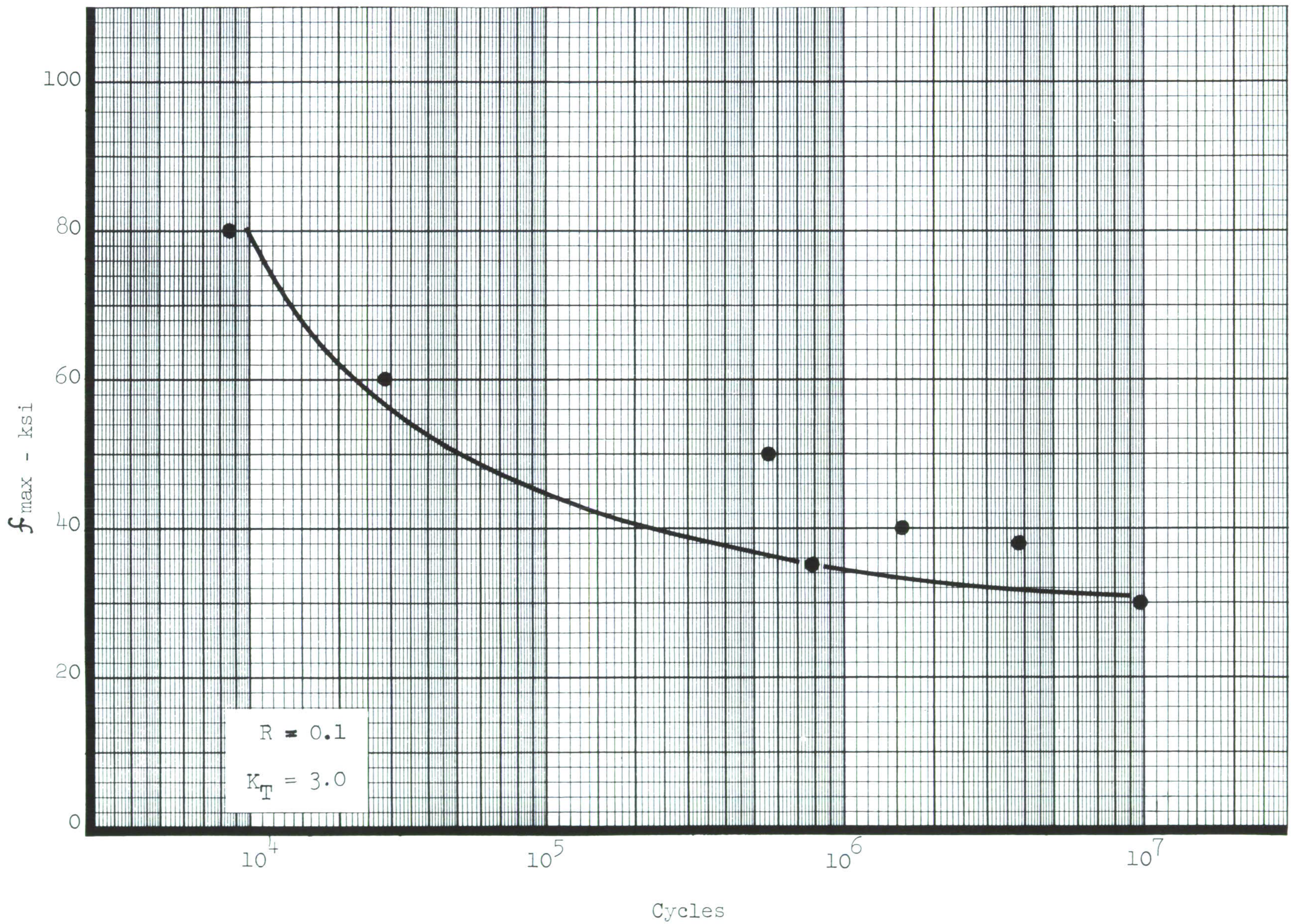


Figure 42. IMI 679 Room Temperature Notched Fatigue Properties

TABLE 17. Ti-6AL-4V SMOOTH AXIAL TENSION FATIGUE PROPERTIES

Forging Number	Specimen Number	Grain Dir.	Test Temp. °F	Stress (1) max. - ksi	Cycles To Failure
#1	H10	L	RT	140.0	35,640
	H9			120.0	71,820
	H11			100.0	111,780
	H12			90.0	1,590,120
	H13			87.0	130,140
	H14			80.0	428,940
	H16			77.0	5,271,840
	H15			75.0	10,000,000 (2)
#2	I54	ST	RT	82.3	394,922
	I53			80.0	3,153,600
	I52			77.0	10,314,360 F
Billet Forging Stock	V1	L	RT	90.0	102,780
	V2			76.0	737,100
	V3			73.0	320,760
	V4			68.0	706,860
#3	IEV	L	550F	120.0	1,260
	H18			100.0	49,500
	H19			99.0	8,280
	H20			90.0	114,840
	H17			80.0	956,160
	H21			78.0	2,212,920
	H22			77.0	3,506,220
	1EW			74.0	10,000,000 (2)

(1) Stress Ratio R = 0.1
(2) No Failure
F Failed

TABLE 18. Ti-6AL-4V NOTCHED AXIAL TENSION FATIGUE PROPERTIES

Forging Number	Specimen Number	Grain Dir.	Test Temp. °F.	Stress (1) max. - ksi	Cycles To Failure
#3	HN1	L	RT	60	20,520
	HN2			40	52,560
	HN8			37	1,022,040
	HN3			35	412,380
	HN4			32	308,520
	HN5			30	4,866,300
	HN6			28	2,614,860
	HN7			26	10^7 N.F.

(1) Stress Ratio R = 0.1, K_t = 3.0

TABLE 19. IMI 679 SMOOTH AXIAL TENSION FATIGUE PROPERTIES

Forging Number	Specimen Number	Grain Dir.	Test Temp. °F.	Stress[(1)] max. - ksi	Cycles To Failure
#1	F11	L	RT	140	2,160
	F9			120	736,920
	F10			115	764,460
	F12			110	1,189,980
	F13			108	858,240
	F14			104	1,756,440
	F15			102	4,773,600
	F16			100	4,896,720
#2	G53	ST	RT	104	1,656,540
	G52			100	2,402,100
	G54			96	2,565,000
Billet Forging Stock	M1	L	RT	110	77,040
	M2			96	621,720
	M4			92	905,580
	M3			90	50,040
#3	F17	L	550 F	100	15,480
	GEV			94	200,880
	F19			92	25,380
	F22			90	1,503,900
	GEW			85	5,423,580
	F18			80	21,780
	F21			77	3,259,800
	F20			70	6,407,460

(1) Stress Ratio R = 0.1

TABLE 20. IMI 679 NOTCHED AXIAL TENSION FATIGUE PROPERTIES

Forging Number	Specimen Number	Grain Dir.	Test Temp. °F.	Stress(1) max. - ksi	Cycles to failure
#3	FN1	L	RT	80	8,640
	FN2			60	28,440
	FN6			50	562,500
	FN3			40	1,583,460
	FN4			38.2	3,845,160
	FN7			35	781,200
	FN8			30	9,721,260
	FN5	Lost in Test			

(1) Stress Ratio $R = 0.1$, $K_t = 3.0$

THERMAL EXPOSURE

In addition to the evaluation of thermal exposure effects on fracture toughness discussed above, smooth and notched tensile specimens of each material were also exposed for one thousand hours at 550°F and tested at room temperature. The data obtained are presented in Table 21 along with the unexposed control values. All exposure testing was conducted on unstressed specimens.

After exposure to 550°F for 1,000 hours, no apparent effect of exposure was noted in either the smooth or notched IMI 679 or Ti-6Al-4V tensile specimens. Two of the four Ti-6Al-4V smooth tensile specimens which were subjected to thermal exposure showed no change in properties while the two other specimens showed a slight increase in strength. This difference, however, is considered to be within the scatter for this alloy.

TABLE 21 ROOM TEMPERATURE LONGITUDINAL TENSILE PROPERTIES BEFORE AND AFTER EXPOSURE

Material and Forging	Exposure Condition	Specimen Number	Type of Specimen	Ultimate Tensile Strength ksi	Yield Strength 0.2% ksi	Elong. % 1 inch	R.A. %
Ti-6Al-4V Forging No. 1	1000 hrs at 550°F	H 32	Smooth	148	135	12	35
		H 36		149	137	12	31
		Average		148.5	136.0	12.0	33.0
	None	Average	Smooth	146.5	133.0	12.3	28.0
	1000 hrs at 550°F	H 54	Smooth	160	150	13	40
		H 55		160	148	14	40
		Average		160.0	149.0	13.5	40.0
	None	Average	Smooth	153.0	141.2	14.0	36.0
	1000 hrs at 550°F	H 52	Notched	218			
		H 53		212			
		Average		215.0			
	None	Average	Notched	213.9			
IMI 679 Forging No. 1	1000 hrs at 550°F	F 32	Smooth	142	129	12	41
		F 36		142	129	14	37
		Average		142.0	129.0	13.0	39.0
	None	Average	Smooth	142.0	127.9	15.7	40.3
	1000 hrs at 550°F	F 54	Smooth	148	136	16	37
		F 55		151	138	14	34
		Average		149.5	137.0	15.0	35.5
	None	Average	Smooth	146.0	133.1	14.7	39.7

TABLE 21 (Cont)

Material and Forging	Exposure Condition	Specimen Number	Type of Specimen	Ultimate Tensile Strength ksi	Yield Strength 0.2% ksi	Elong. % 1 inch	R.A. %
IMI 679	1000 hrs at 550°F	F 52	Notched	200			
		F 53		206			
Forging No. 1 (cont)		Average		203.0			
	None	Average	Notched	207.0			

MODULUS OF ELASTICITY

A Tuckerman optical strain measuring system was used to develop precision room temperature tension and compression elastic modulus data on Ti-6Al-4V and IMI 679. Since modulus data were not obtained in the previous program, the Ti-13V-11Cr-3Al and Ti-6Al-6V-2Sn alloys were also tested as part of this program. Specimens were taken in the longitudinal and long transverse grain directions from a slab similar to block VII of forging No. 3.

Tension and compression modulus of elasticity data for all four alloys are presented in Tables 22 and 23. No significant difference in modulus was noted between the longitudinal and long transverse grain directions in any of the alloys tested. Of the four alloys tested the Ti-6Al-4V exhibited the highest tension modulus and compression modulus values.

A second set of tests was run on each specimen of the Ti-6Al-4V and IMI 679. Data from the second test were in excellent agreement with the values reported in Tables 22 and 23.

TABLE 22 THICK SECTION TENSION MODULUS OF ELASTICITY TESTS(1)

Alloy	Specimen Location	Grain Direction	Modulus (10^6 psi)
IMI 679	Edge	L	15.6
			15.8
			15.7
		Average	15.7
		LT	15.6
			16.3
			16.4
		Average	16.1
Ti-6Al-4V		L	17.0
			17.1
			17.2
		Average	17.1
		LT	17.2
			17.2
			17.4
		Average	17.3
Ti-13V-11Cr-3Al		L	16.1
			15.6
			15.3
		Average	15.7
		LT	15.4
			15.7
			14.9
		Average	15.3
Ti-6Al-6V-2Sn		L	15.8
			15.9
			15.8
		Average	15.8
		LT	16.4
			16.4
			16.2
		Average	16.3

(1) Tuckerman gages were used to establish modulus values

TABLE 23 THICK SECTION COMPRESSION MODULUS OF ELASTICITY TESTS[1]

Alloy	Specimen Location	Grain Direction	Modulus (10^6 psi)
IMI 679	Edge	L	16.0
			16.0
			16.2
		Average	16.1
		LT	16.5
			16.5
		Average	16.5
Ti-6Al-4V		L	17.4
			17.4
			17.3
		Average	17.4
		LT	17.2
			17.2
			17.6
		Average	17.3
Ti-13V-11Cr-3Al		L	16.0
			16.2
			15.9
		Average	16.0
		LT	15.4
			15.5
			15.6
		Average	15.5
Ti-6Al-6V-2Sn		L	16.2
			16.2
			16.2
		Average	16.2
		LT	17.0
			16.6
			17.0
		Average	16.9

(1) Tuckerman gages were used to establish modulus values

ENVIRONMENTAL DELAYED FAILURE EVALUATION

Certain titanium alloys and heat treat conditions are known to be susceptible to delayed failure in the presence of a crack, stress and salt water. Therefore, a limited evaluation was conducted to determine the susceptibility to delayed failure in salt water of forged Ti-6Al-4V and IMI 679. Section size has previously been shown to have an important influence on material susceptibility, therefore, in this study samples were taken from the relatively thin web areas as well as from the forging center section in each alloy.

All specimens were oriented in the long transverse grain direction. Pre-cracked, notched bend bars were tested using the procedure described in Appendix III. The conventional plane strain, fracture toughness, K_{1c}, was determined for each set of samples in air. Then a sustained load limit in salt water was established and used to calculate the sustained load, environmenta, stress intensity limit K_{1i}. The ratio of K_{1c} to K_{1i} can then be used to indicate the relative material susceptibility to delayed failure in salt water.

The test results are reported in Table 24. These data indicate a relatively high resistance to delayed failure for both heavy and light section Ti-6Al-4V and light section IMI 679 material. The IMI 679 from the heavy center location exhibited substantial susceptibility. The ratio of $\frac{K_{1i}}{K_{1c}}$ for this material was 57% whereas all other materials exceeded 75%. In previous work the rate of cooling from the solution temperature has been found to affect delayed failure susceptibility of titanium alloys. This may explain the difference in the behavior between the Ti-6Al-4V and IMI 679 taken from the forging heavy sections. The IMI 679 was solution treated in full section size and forced air cooled. In contrast with this relatively slow cooling rate in the IMI 679, the Ti-6Al-4V material was only 3/4 inches thick at time of heat treatment and was water quenched.

The K_{1c} values obtained with the notched bend specimens and reported in Table 24 are noted to be significantly higher than the K_{1c} values obtained with pre-cracked, notched round bar specimens reported in Tables 15 and 16. The differences are inherent in the two different types of fracture toughness testing techniques.

TABLE 24 DELAYED FAILURE RESISTANCE IN SALT WATER[1]

Alloy	Specimen Location	Specimen Number	Nominal Breaking Stress		Time to Failure	K_{1c} [2] (ksi $\sqrt{in}$)	K_{1i} [3] (ksi $\sqrt{in}$)	$\frac{K_{1i}}{K_{1c}}$
			Air Pop-in (ksi)	Salt Water (ksi)				
Ti-6Al-4V	Center	V1	159			64		
		V2	137			54		
		V3		147	Broke on loading			
		V4		146	Broke on loading			
		V5		136	Broke on loading			
		V6		130	No Failure		50	.85
		V7		95	No Failure			
	Web	V8	161			64		
		V9	157			62		
		V10		151	1 min			
		V11		132	No Failure		53	.84
		V12		112	No Failure			
		V13		104	No Failure			
		V14		83	No Failure			
IMI 679	Center	M1	167			68		
		M2	160			65		
		M3		159	Broke on loading			
		M4		121	6 min			
		M5		118	6 min			
		M6		109	3 min			
		M7		94	No Failure		37	.56

TABLE 24 (Cont)

Alloy	Specimen Location	Specimen Number	Nominal Breaking Stress		Time to Failure	K_{1c} (2) (ksi $\sqrt{in}$)	K_{1i} (3) (ksi $\sqrt{in}$)	$\frac{K_{1i}}{K_{1c}}$
			Air Pop-in (ksi)	Salt Water (ksi)				
IMI 679 (Cont)	Web	M8	163			66		
		M9	162			64		
		M10		136	1 min			
		M11		125	No Failure		51	.78
		M12		121	No Failure			
		M13		107	No Failure			
		M14		96	No Failure			

(1) All values obtained with bend specimen shown in Figure 90.

(2) Control value obtained in air.

(3) Sustained load environmental stress intensity limit. Calculated from bend specimen fracture toughness equation.

METALLURGICAL EVALUATION

Metallographic studies were conducted on the Ti-6Al-4V and IMI 679 forgings. Representative sections were taken from web and center locations in each alloy to show transverse and longitudinal grain structure.

Microstructures of Ti-6Al-4V forgings are presented in Figures 43 through 46. Longitudinal and transverse views in the web area are given in Figures 43 and 44. respectively. The Ti-6Al-4V shows little evidence of directionality in either the web or center section. Microstructure in the Ti-6Al-4V consisted of primary alpha in a transformed beta matrix. The specimen from the center section shows a greater amount of martensitic alpha than the web specimen. Normally, martensitic alpha indicates a faster cooling rate. This is possible since the specimens in Figures 45 and 46 were taken near the quenched surface of the thick section.

The Ti-6Al-4V starting billet microstructure is shown in Figure 47. The coarse, accicular alpha present in the billet has been altered significantly in the forgings as a result of the working and heat treatment received by the forgings.

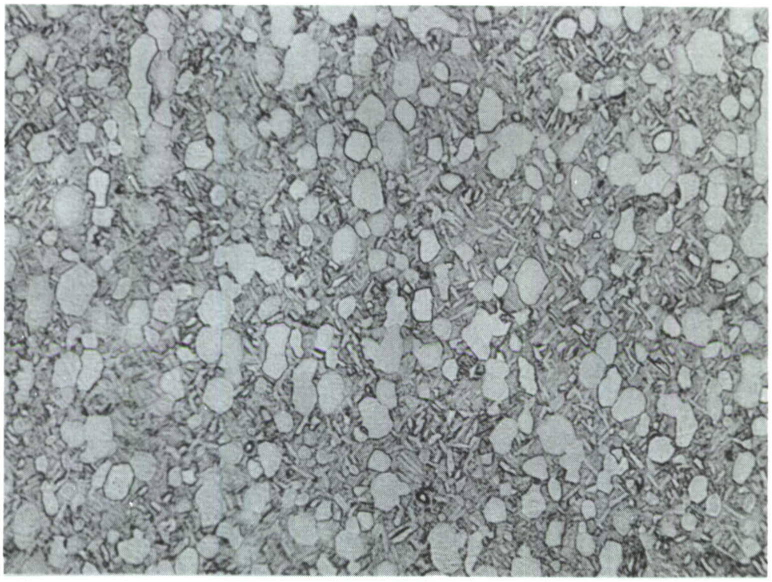
Figures 48 and 49 show the microstructure for two grain directions in the relatively thin web section of IMI 679 forgings. The web area in the forging received considerably more work than the heavy center section; however, the microstructures are quite similar in both locations. See Figures 50 and 51. None of the microstructures exhibit significant directionality. In each case, the metallurgical structure consists of primary alpha (light areas), transformed beta, and silicides (dark particles). All of these microstructures are noted to be finer than corresponding microstructures in the Ti-6Al-4V forging.

The IMI 679 billet microstructure is shown in Figure 52. As was the case with Ti-6Al-4V, the coarse elongated alpha particles present in the billet have been altered significantly in the forgings as a result of the working and heat treatment received by the forgings.

Figures 53 and 54 show the macrostructure obtained in a transverse web and flange area in Ti-6Al-4V and IMI 679 respectively. Considerable refinement of structure is noted compared to the center sections. The forging flow lines are typical of the section shown.

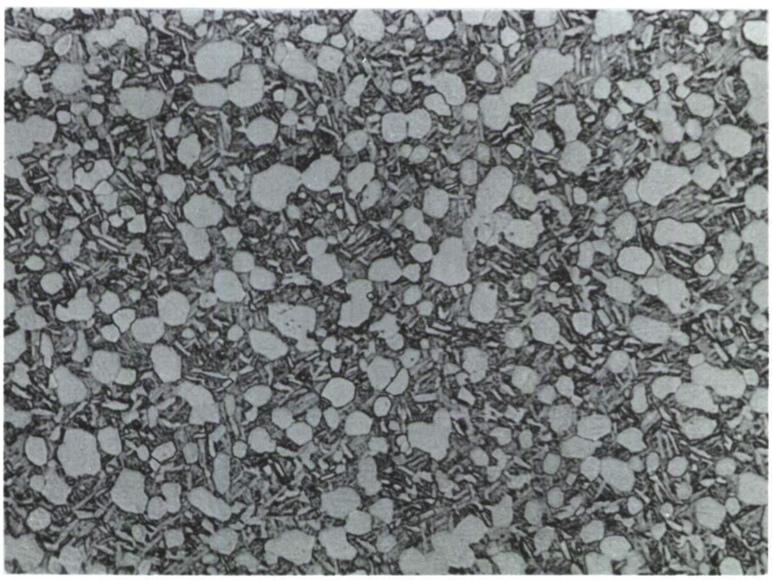
Longitudinal and transverse macrosections of the forging heavy sections of each alloy are shown in Figures 55 through 58. These figures can be compared to the billet macrostructures (see Figures 74 through 77, Appendix I) to determine metallurgical changes related to crossworking, forging and heat treatment operations. Similar to the findings in Reference 1, the macrosections indicate considerable grain refinement near the forging surfaces in each alloy with only small changes noted in the forging center sections.

The unusual ring pattern in the IMI 679 macrographs is apparently typical of this alloy. TMCA has reported the same type of pattern in IMI 679 and stated that it is a carry over from the ingot macrostructure. Electron microprobe analysis of these patterns have been made by TMCA. The results showed no chemical segregation and it is believed that the pattern is strictly an orientation effect (5).



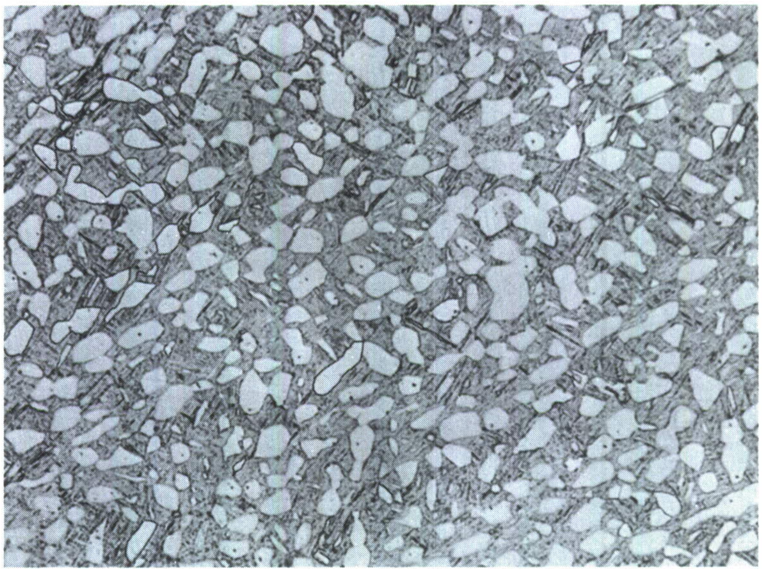
Forging Web Area

Figure 43. Ti-6Al-4V Microstructure of Specimen HAO, Longitudinal Grain Direction (250X)



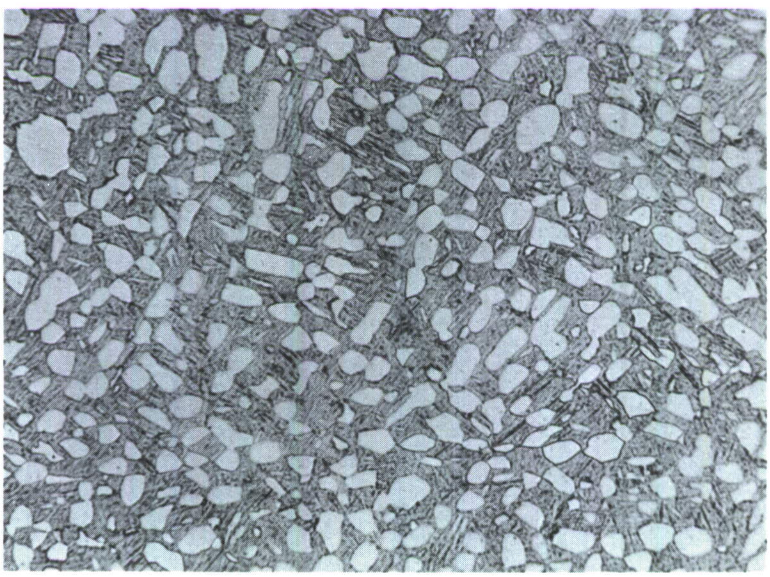
Forging Web Area

Figure 44. Ti-6Al-4V Microstructure of Specimen HAO, Transverse Grain Direction (250X)



Forging Heavy Section

Figure 45. Ti-6Al-4V Microstructure of Specimen H-67 Longitudinal Grain Direction (250X)



Forging Heavy Section

Figure 46. Ti-6Al-4V Microstructure of Specimen H-67 Transverse Grain Direction (250X)

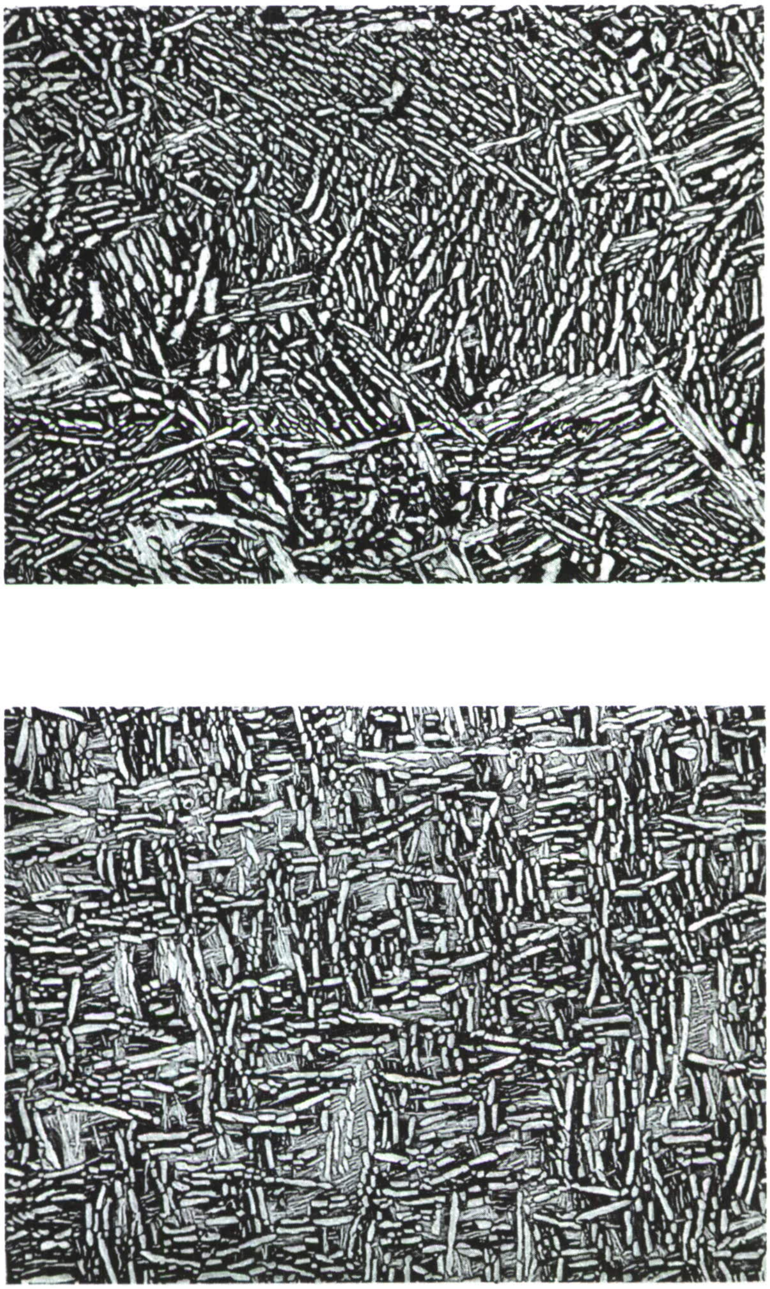
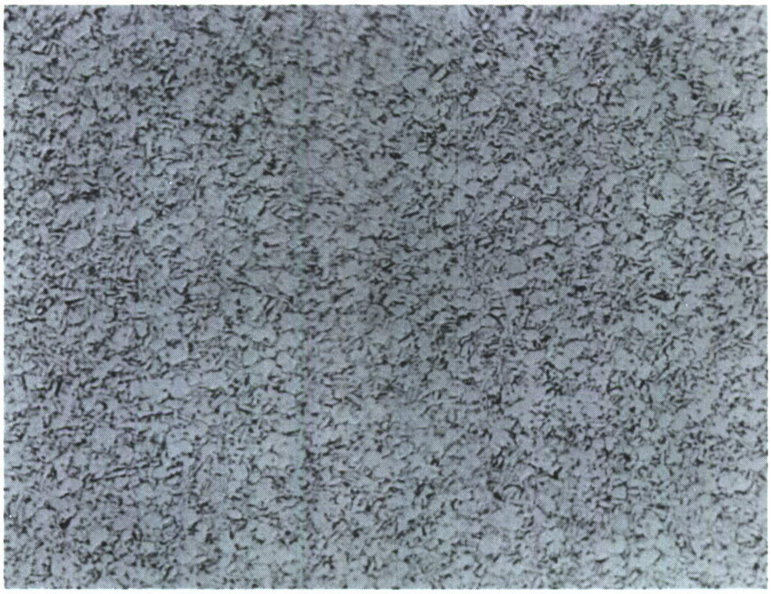
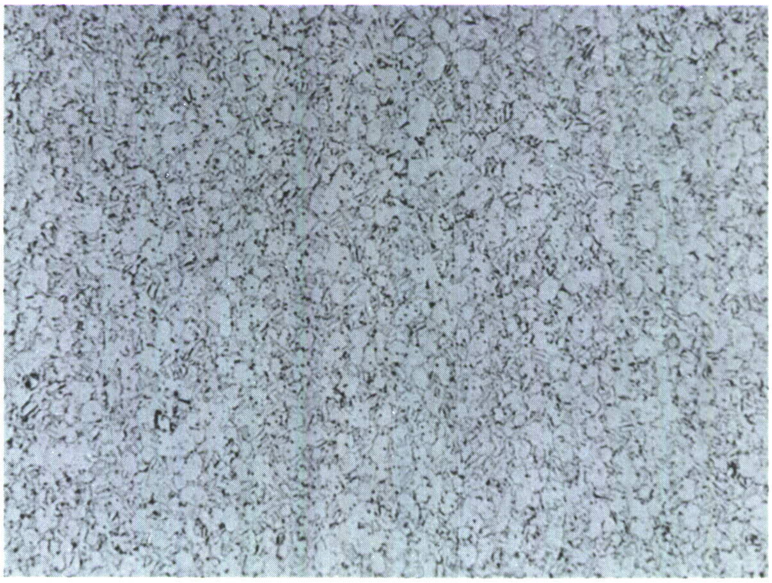


Figure 47. Microstructure of Heat Treated Ti-6Al-4V Billet Stock (Longitudinal - Upper, Transverse - Lower) (100X) Etchant: NAOH



Forging Web Area

Figure 48. IMI 679 Microstructure of Specimen FAO Longitudinal Grain Direction (250X)

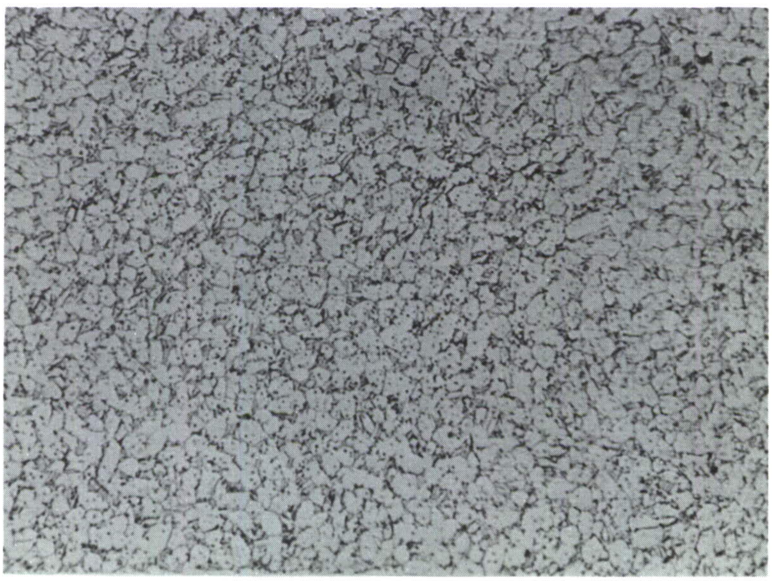


Forging Web Area

Figure 49. IMI 679 Microstructure of Specimen FAO Transverse Grain Direction (250X)

Forging Heavy Section

Figure 50. IMI 679 Microstructure of Specimen F-58 Longitudinal Grain Direction (250X)



Forging Heavy Section

Figure 51. IMI 679 Microstructure of Specimen F-58 Transverse Grain Direction (250X)

Figure 52 Microstructure of Heat Treated IMI 679 Billet Stock
(Longitudinal - Upper, Transverse - Lower)
Etchant: Benzal Stain (250 X)

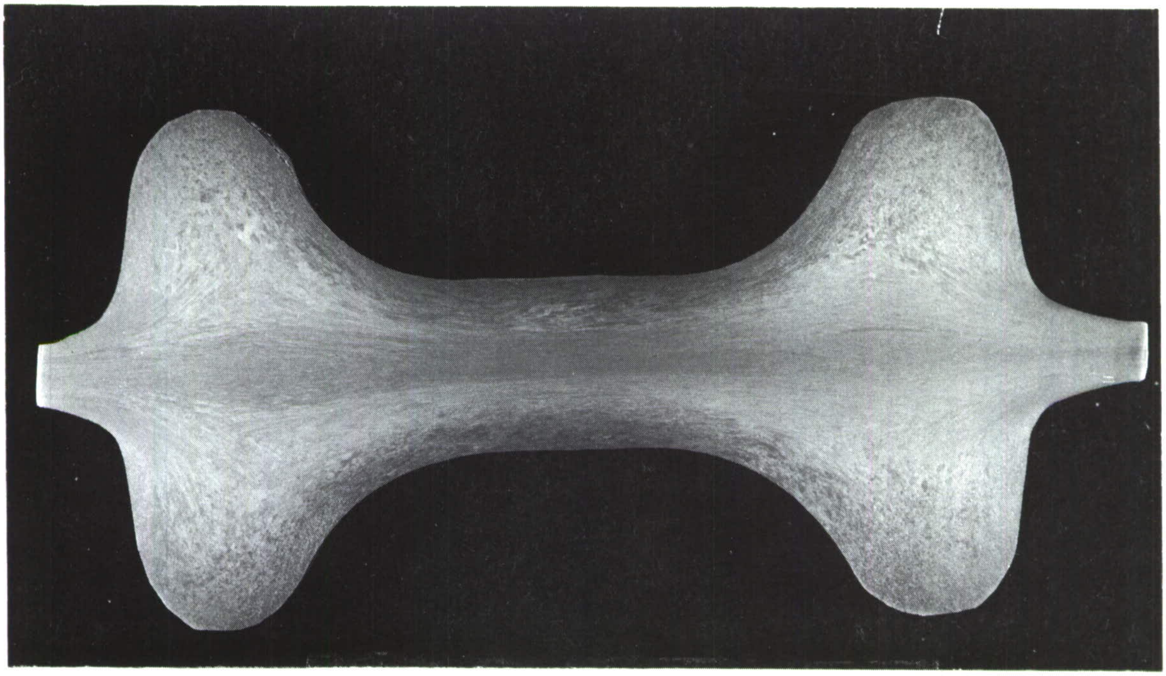


Figure 53 Ti-6Al-4V Macrostructure of Transverse Web and Flange Area

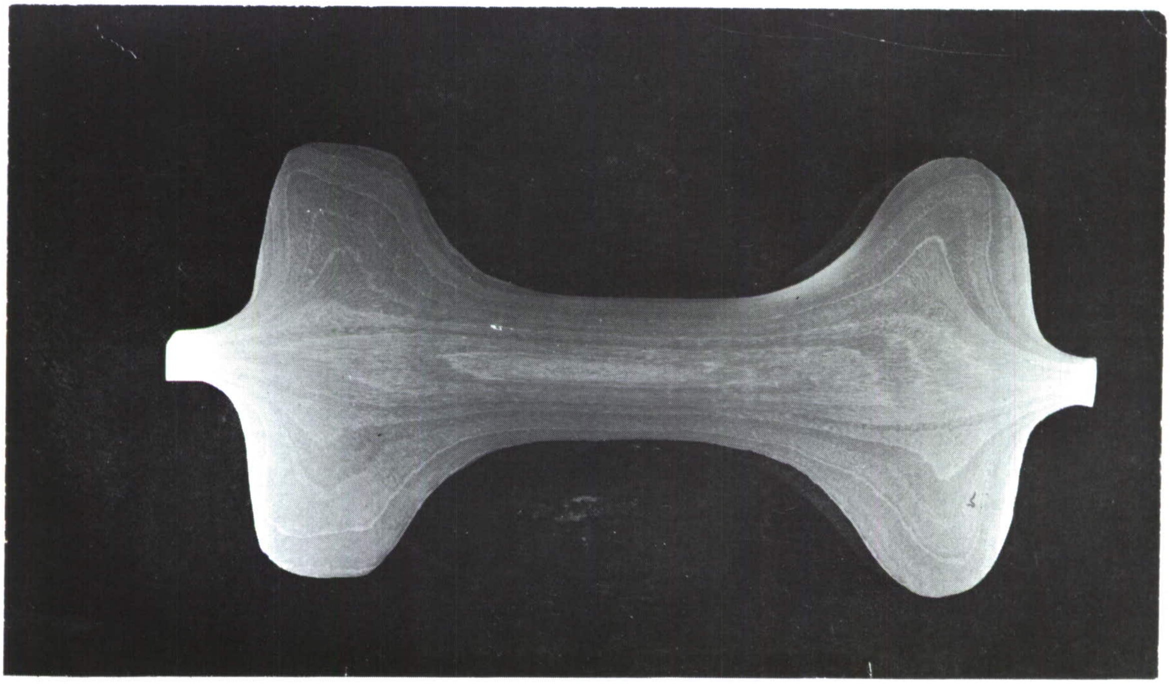


Figure 54. IMI 679 Macrostructure of Transverse Web and Flange Area

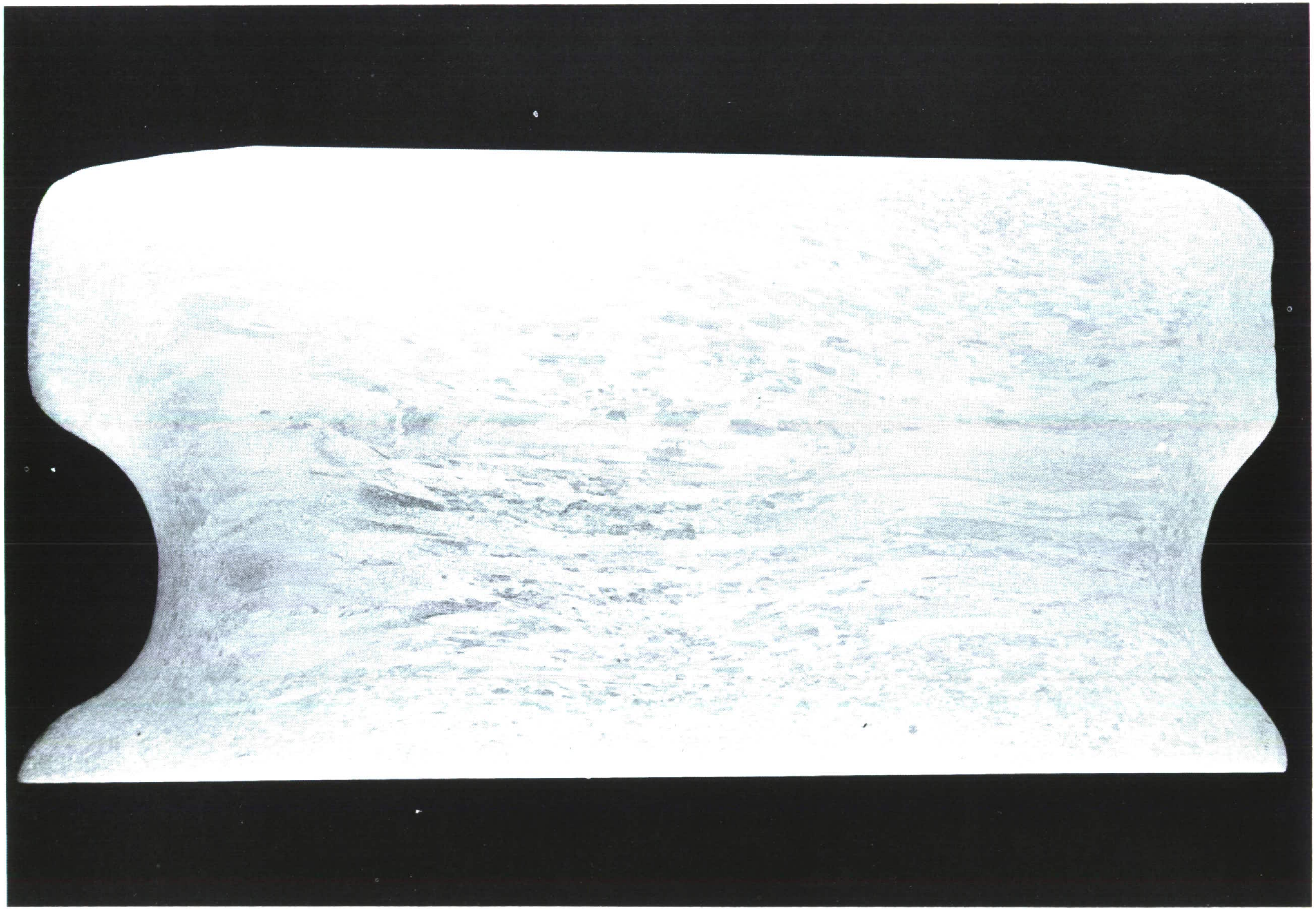


Figure 55 Ti-6Al-4V Longitudinal Section Through Forging Center Section (Approx. 1X)

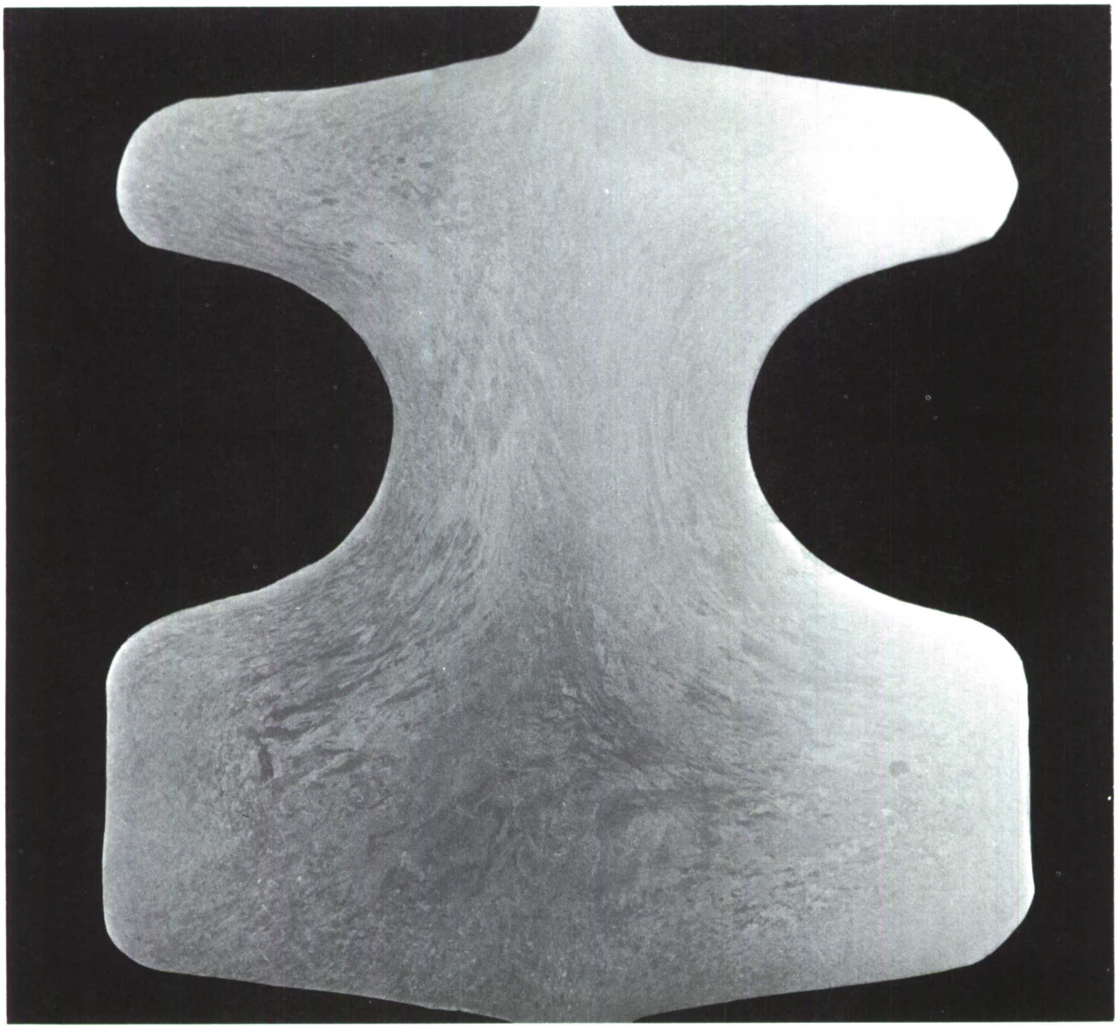


Figure 56 Ti-6Al-4V Transverse Section Through Forging Center Section (Approx. 1X)

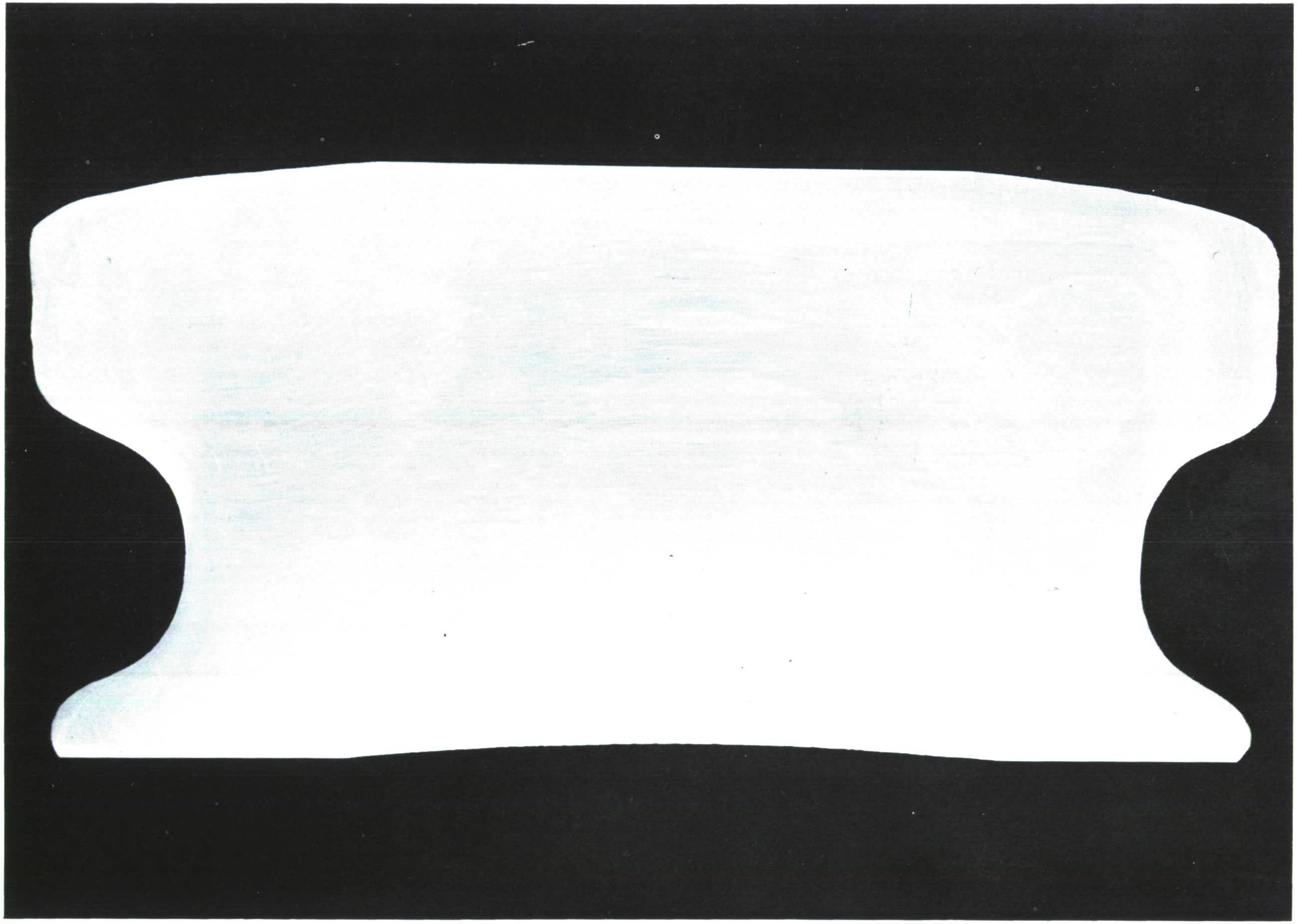


Figure 57 IMI 679 Longitudinal Section Through Forging Center Section (Approx. 1X)

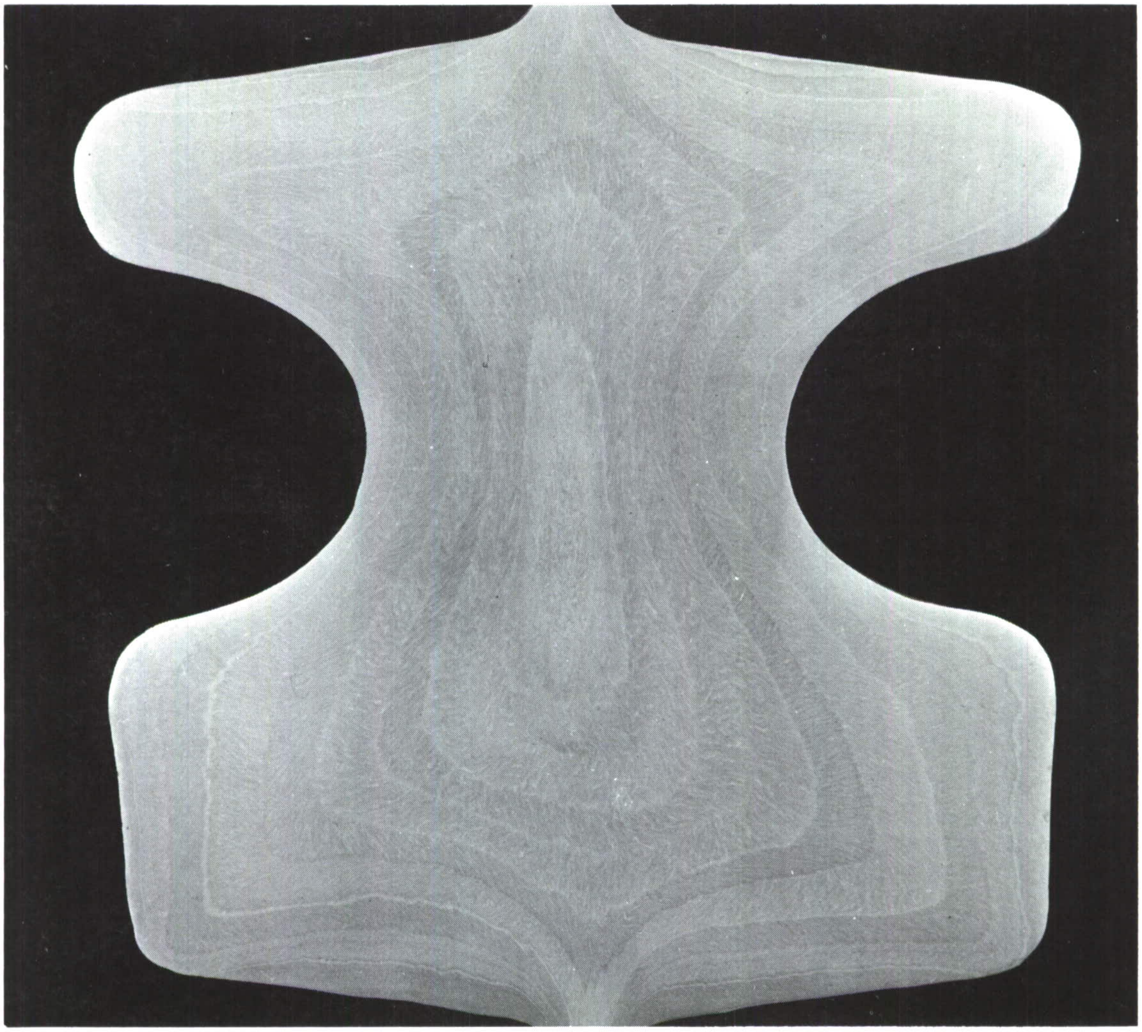


Figure 58 IMI 679 Transverse Section Through Forging Center Section (Approx. 1X)

Section V

FORGING STATIC TEST

The forging static test program consisted of testing one machined fuselage ring fitting of Ti-6Al-4V and one of IMI 679. This part was originally selected in the previous program to represent a typical airplane forging design which includes local effects of skin attachment holes, fin to spar attachment lugs, and curved flanges following fuselage contour. The static test procedure consisted of an up-load in combination with a side load which produced complex loading in the parts. The direction of these loads are related to those experienced in an actual part in an airplane.

In the test set-up, the forging was supported at each end by flexure pivots attached to the end fittings. The vertical load was applied equally by two jacks and the side load by one jack. The vertical components were reacted through the flexures and the side load was reacted by a tension strap attached to the top deck of the forging. Test loads were applied in increments until failure. The test set-up is shown schematically in Figure 59. A view of the actual test set-up with a forging installed for test is shown in Figure 60.

Dial gages were located 3 inches on either side of the forging centerline. The test loads were applied in increments and deflections measured for various loadings up to 25,000 pounds. The load was returned to zero and the dial gages were re-checked for evidence of permanent set in the parts. Neither alloy showed evidence of permanent set after application of the 25,000 pound load which is approximately 70 percent of the predicted failure strength. Test loads were then re-applied in increments to failure. Load-deflection data are presented in Table 25.

The load deflection curves for each part are shown in Figure 61. These curves can be compared to those obtained on Ti-6Al-6V-2Sn, Ti-13V-11Cr-3Al, and 4340 steel parts (Ref. 1). Such a comparison shows that the Ti-6Al-4V and IMI 679 parts were stiffer than parts made from the other two titanium alloys. This difference was due primarily to the increased thickness dimensions of the Ti-6Al-4V and IMI 679 parts rather than significant differences in elastic modulus.

The static test results were as follows:

Alloy	Part Weight	Failure Load (lbs) P_Z (Vertical)	Failure Load (lbs) P_Y (Horizontal)
IMI 679	9.85 lbs	36,500	4,380
Ti-6Al-4V	9.00 lbs	39,500	4,740

Failure initiated in bending in the upper flange in the same location in both materials. The Ti-6Al-4V part showed almost complete shear mode fracture. The IMI 679 part had less than 15% shear type fracture. The Ti-6Al-4V and IMI 679 fractured parts are shown in Figures 62 and 63, respectively.

These results (Table 25) can be compared directly with the results obtained in the previous program since all testing procedures were identical. Static test results from Reference 1 were as follows:

Alloy	Part Weight	Failure Load (lbs) P_Z (Vertical)	Failure Load (lbs) P_Y (Horizontal)
Ti-6Al-6V-2Sn	8.54	39,000	4,680
Ti-13V-11Cr-3Al	9.28	32,500	3,900
4340 Steel (180 ksi H.T.)	14.62	45,000	5,400

In all cases, the titanium alloy forging target was to have strength equal to the 180 ksi, 4340 steel forging design. This was accomplished by increasing critical dimensions in the titanium forgings to compensate for the differences in strengths. Because of differences in the basic strength of the titanium alloys, the dimensional increases in the lower strength Ti-6Al-4V and IMI 679 were proportionately greater than those in the higher strength Ti-6Al-6V-2Sn and Ti-13V-11Cr-3Al. The Ti-6Al-4V and Ti-6Al-6V-2Sn had almost identical breaking strengths and were the highest of the four titanium alloys. Failure strength of the 4340 steel part was substantially greater than any of the titanium parts. As pointed out in Reference 1, a strength check on the steel part indicated an actual ultimate tensile strength of 205 ksi, whereas predicted strength was based on the intended F_{tu} of 180 ksi, which explains the high breaking strength in the steel part.

Figure 64 compares the static strength efficiency (expressed as failure strength divided by part weight) of these parts. Failure strengths for Ti-6Al-4V and IMI 679 are compared in Figure 65. Figures 9 and 10, in the Summary Section, compare the static strength and static strength efficiency of all five alloys.

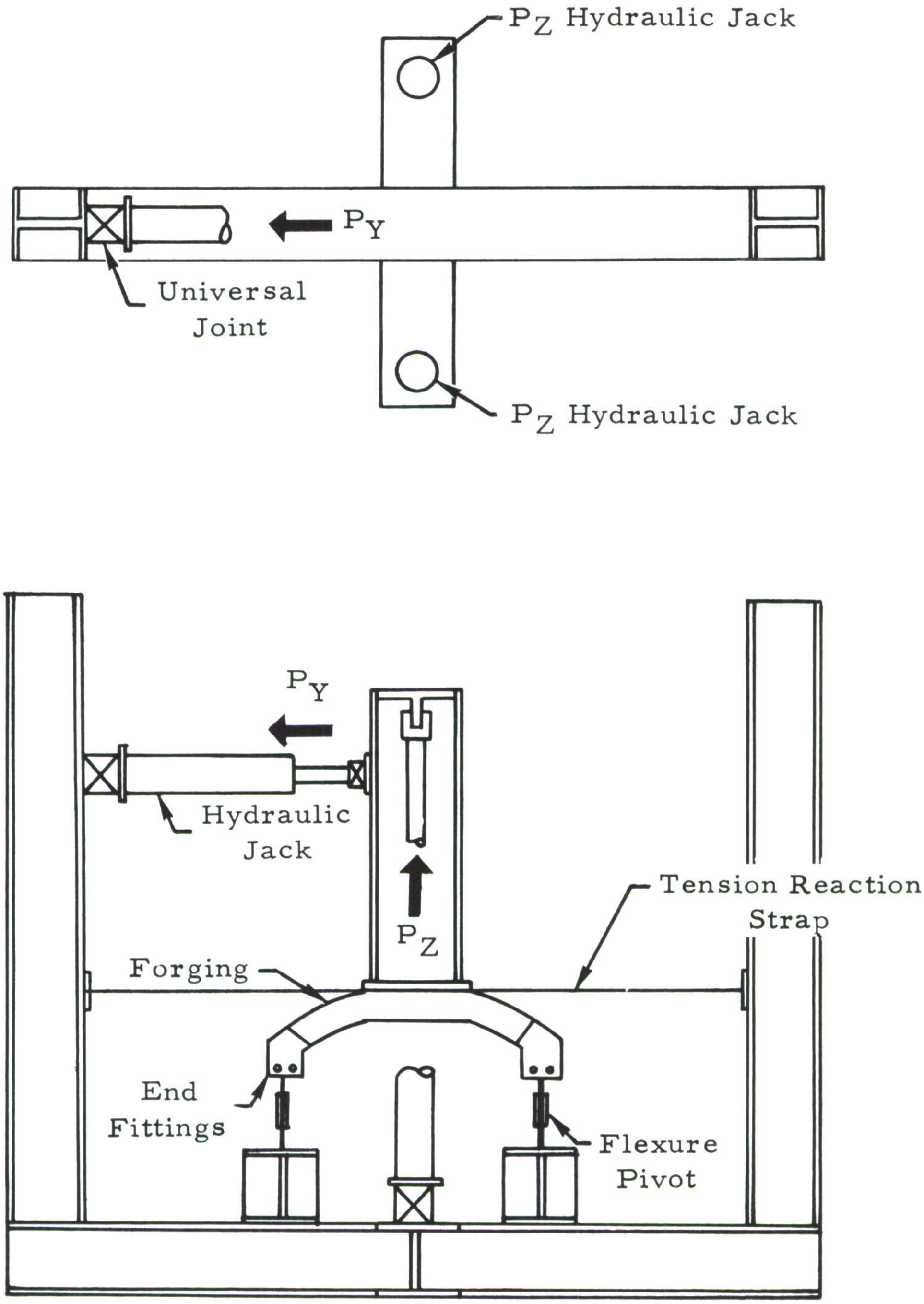


Figure 59. Schematic of Static Test Set-Up

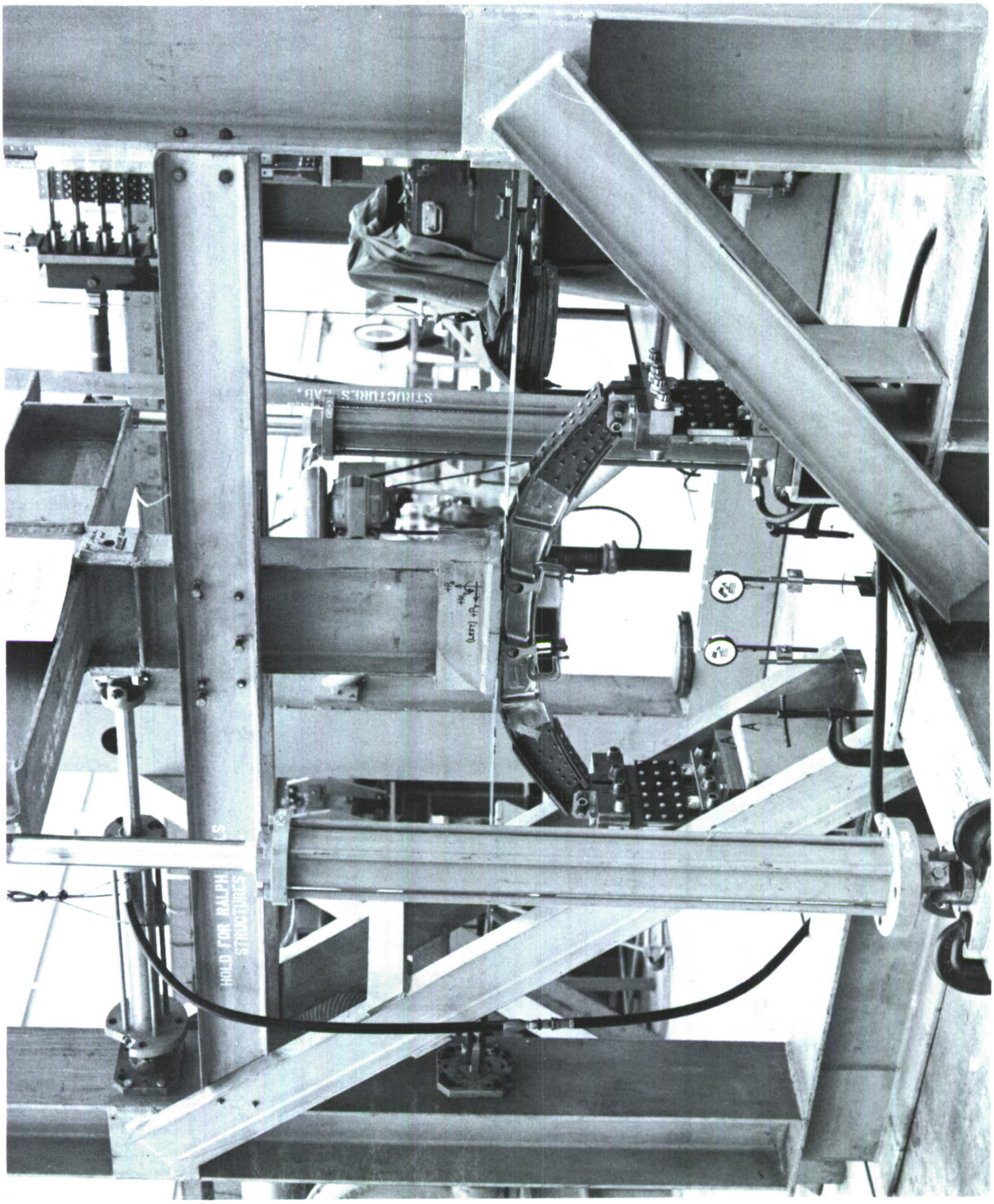


Figure 60. Static Test Set-up

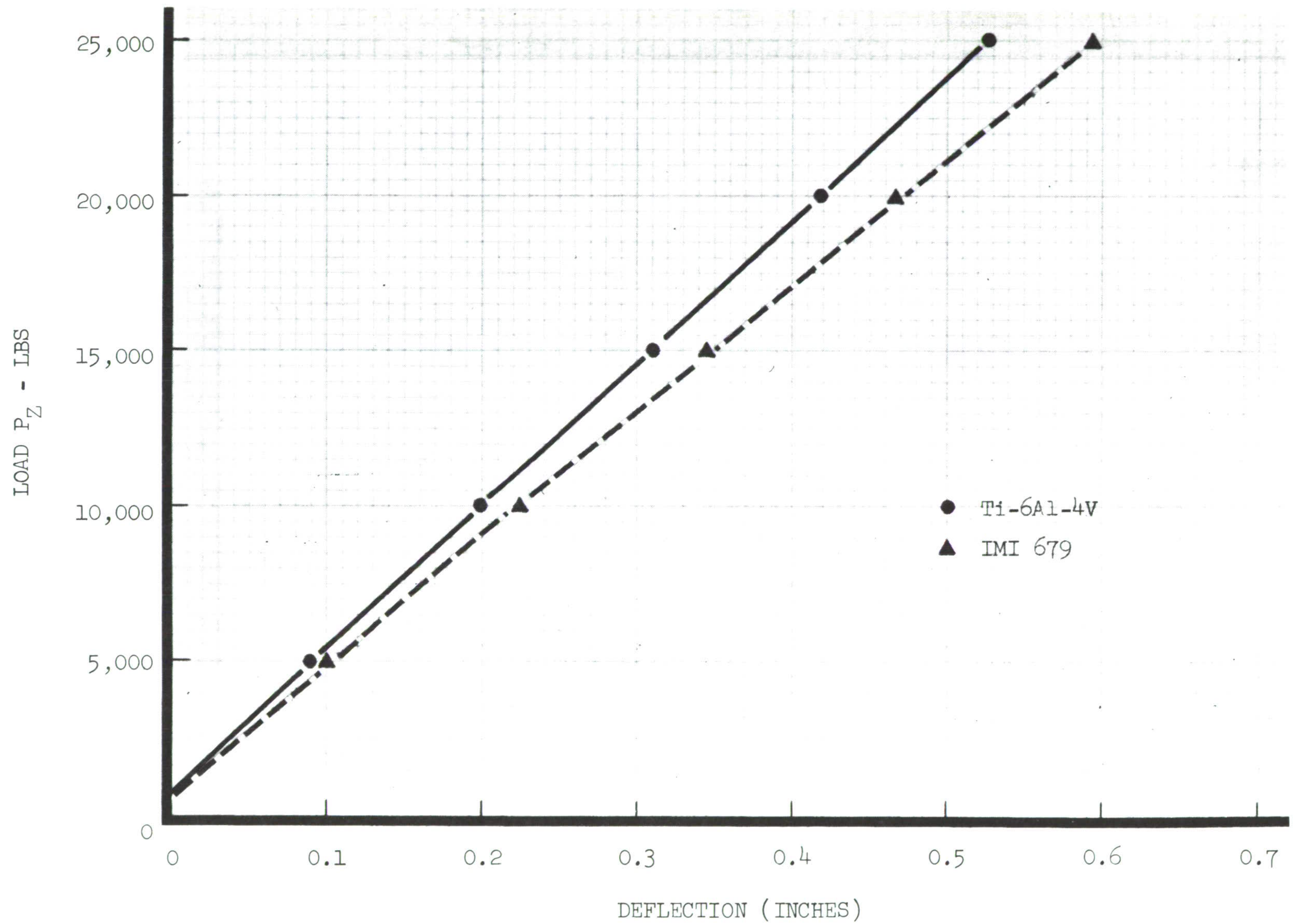


Figure 61. Static Test Load-Deflection

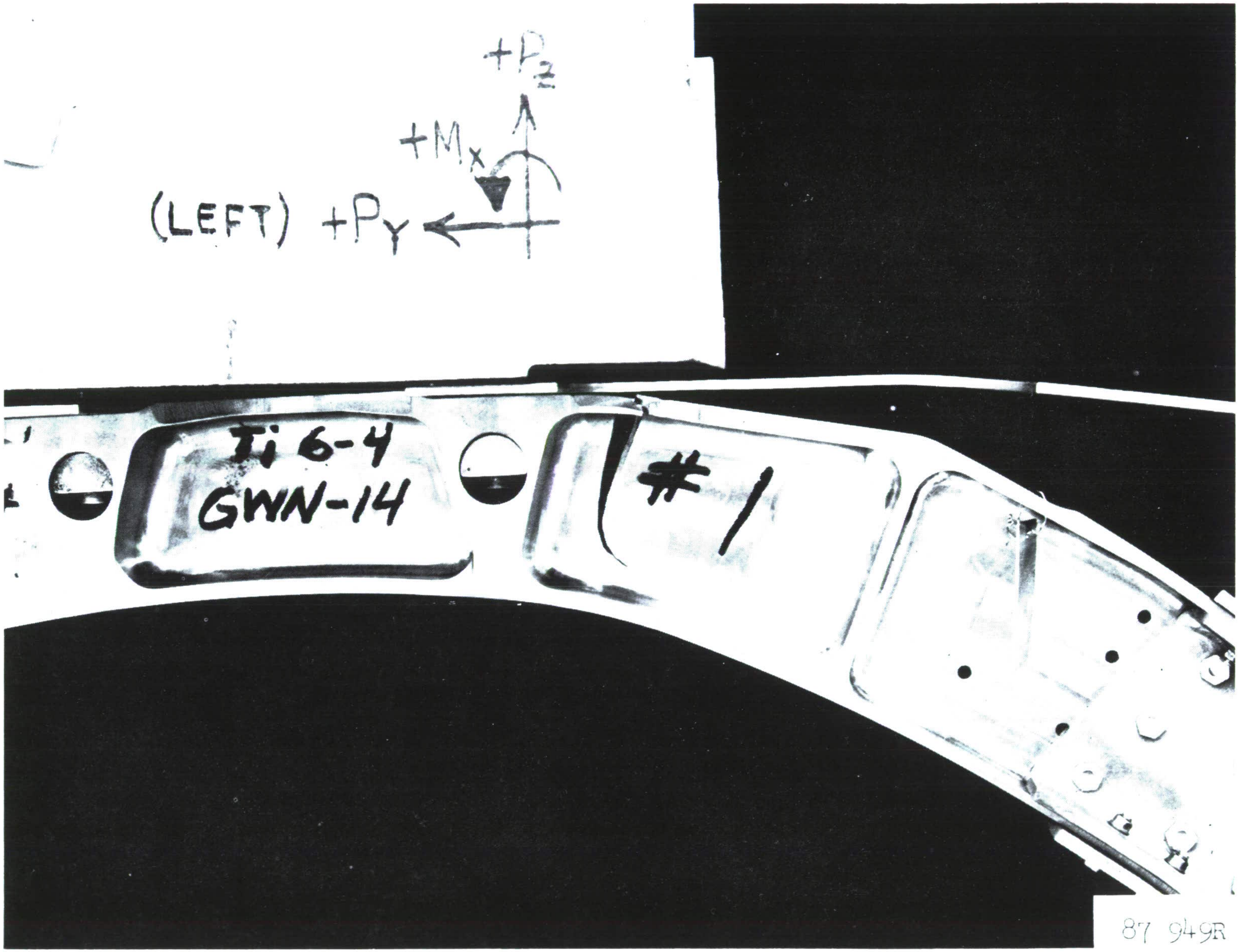


Figure 62. Static Test Failure Ti-6Al-4V

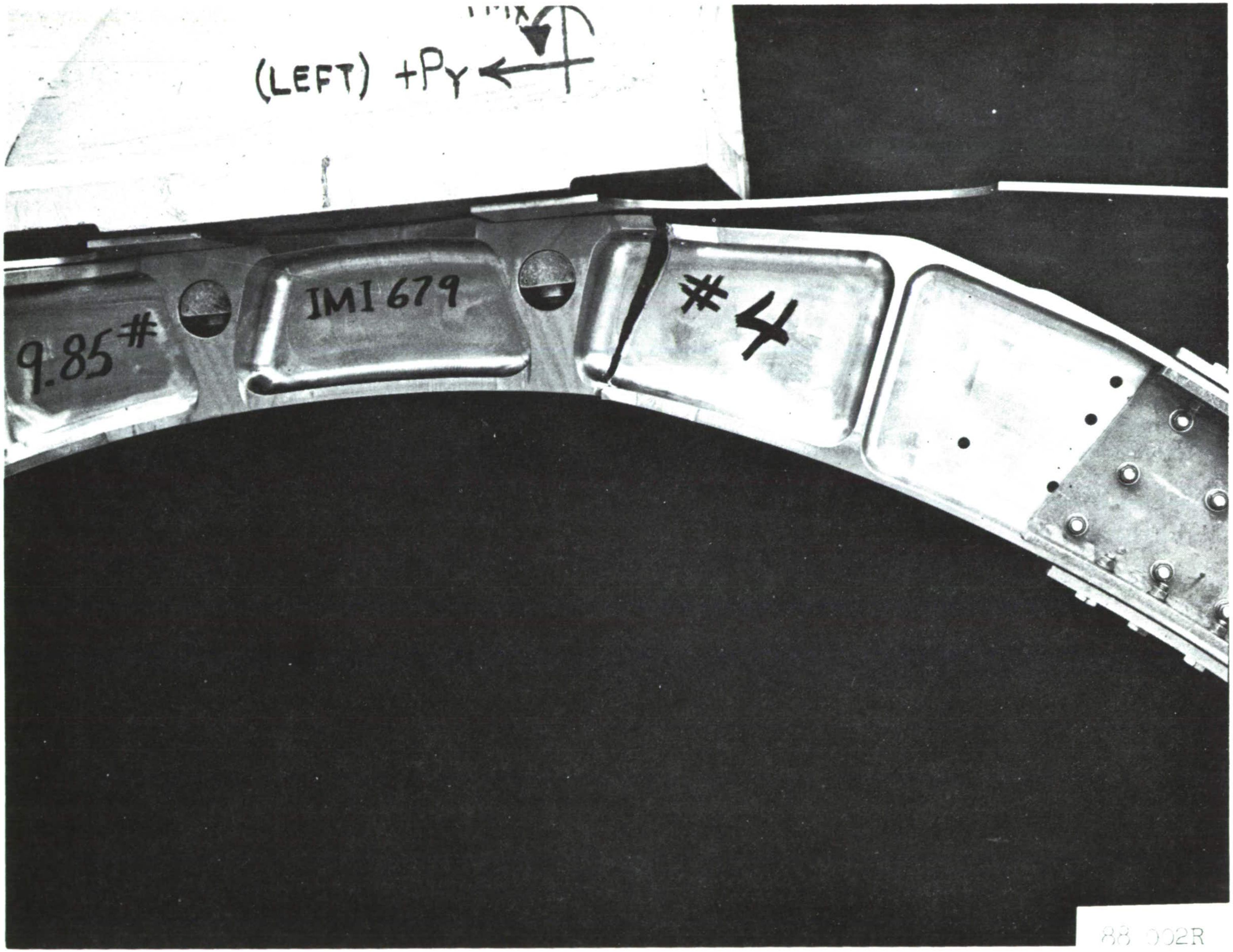
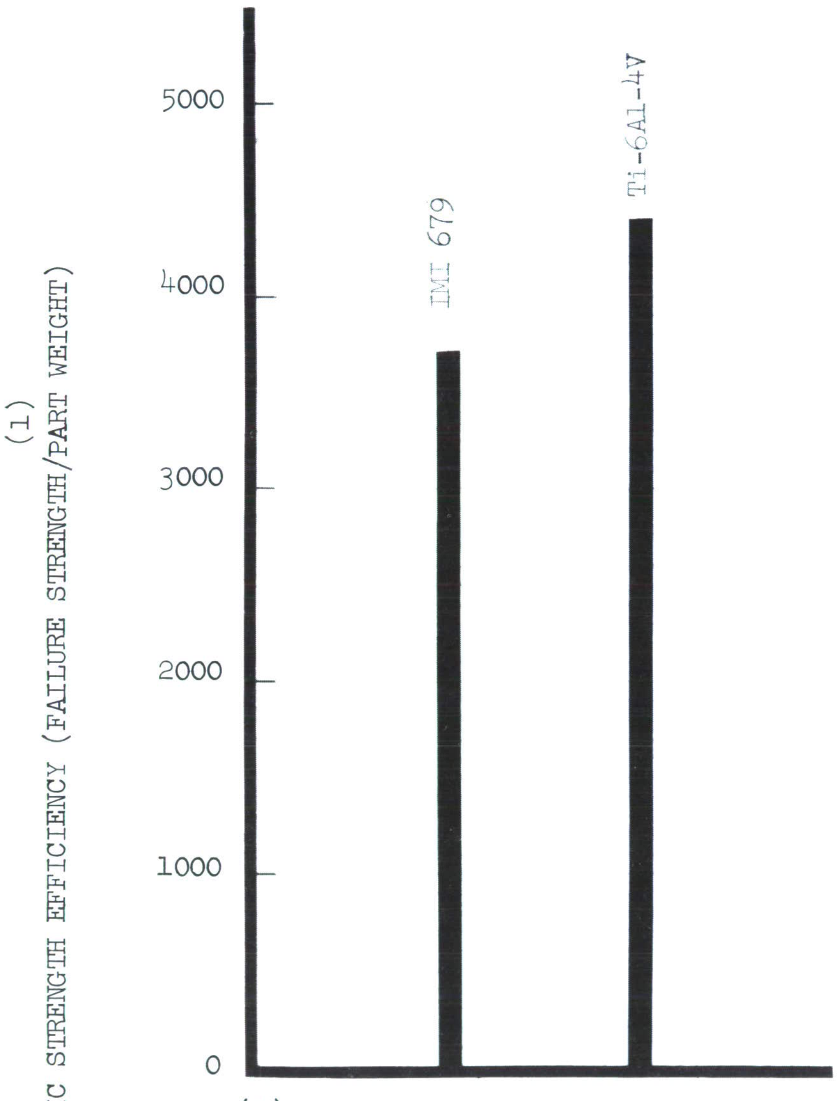


Figure 63. Static Test Failure IMI 679



(1)Based on P_z where P_y = 12% of P_z at all loads

Figure 64. Comparison of Static Strength Efficiency

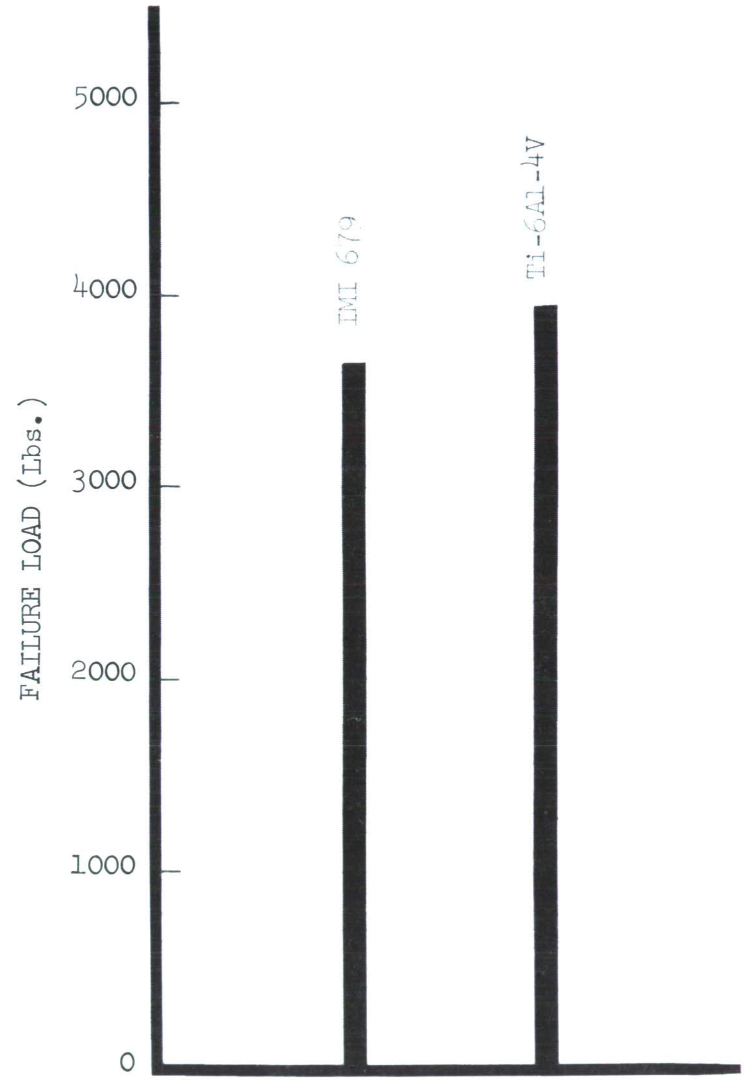


Figure 65. Comparison of Forging Static Stength

TABLE 25 FULL SCALE STATIC TEST RESULTS

Forging Alloy	Weight of Part (lbs)	Applied Load (lbs)		Net Deflection (Inches)
		P_Z	P_Y	
Ti-6Al-4V	9.00	0	0	0
		5,000	600	0.089
		10,000	1,200	0.199
		15,000	1,800	0.310
		20,000	2,400	0.419
		25,000	3,000	0.527
		39,500	4,740	Failed
IMI 679	9.85	0	0	0
		5,000	600	0.100
		10,000	1,200	0.224
		15,000	1,800	0.345
		20,000	2,400	0.466
		25,000	3,000	0.592
		36,500	4,380	Failed

Section VI

FORGING FATIGUE TEST

A full scale fatigue test was conducted on one forging each of IMI 679 and Ti-6Al-4V. The test loading spectrum and test procedure were the same as that used in the Reference 1 program, which permits direct comparisons of test results. (See Summary Section.) The test loading spectrum used was based on the lateral gust spectrum originally specified for application to the vertical fin of an F-104G aircraft, except that the severity of the spectrum was increased to insure failure in a reasonable test time. The fatigue loadings consisted of a varying side load (P_Y) and a mean vertical load (P_Z). The fatigue unit spectrum is shown in Figure 66. Repetitive applications of the unit spectrum were applied until failure occurred.

The forging fatigue test set-up utilized the same basic test fixture that was used for static testing. The mean load and counterbalance of the loading fixture was applied with dead weight. The varying side load was applied by a hydraulic jack and controlled by a Schmitt Trigger. Operation of the Schmitt Trigger consisted of setting trigger points to a particular load level. When the desired load was reached, the voltage feedback from a load cell mounted in series with the hydraulic jack triggered a relay and transferred the hydraulic pressure from one jack port to the other. This cycling continued until a pre-set cycle counter shut off the Schmitt Trigger. The trigger points were reset for each new load level.

The vertical mean load and the vertical components of the M_X moment were reacted through flexure pivots and the P_Y shear loads were reacted alternately by one of two tension straps. The fatigue test set-up and the control system are shown schematically in Figures 67 and 68, respectively. A view of the actual test set-up with a forging installed for test is shown in Figure 69.

Table 26 presents the fatigue loading history of each part. In each case, testing was discontinued shortly after the appearance of visible cracks in the parts. The Ti-6Al-4V part failed in 172,100 cycles, during application of the 4,300 pound P_Y loads, in the seventh application of the unit specimen. The IMI 679 part failed after 278,700 cycles during application of the 3000 pound load in the twelfth application of unit spectrum.

In the IMI 679 part, the fatigue failure initiated at a barrel nut hole as shown in Figure 70. Two different crack locations were found in the Ti-6Al-4V part. The major crack occurred in the web adjacent to the barrel nut holes as shown in Figure 71. A second smaller crack was found in the web immediately inboard of the end attachment fitting. After finding the second crack in the Ti-6Al-4V part, a thorough zyglo inspection was conducted on both parts to determine possible secondary cracks. No other cracks were found in either part.

The lower fatigue life and presence of two cracks in the Ti-6Al-4V part prompted an investigation to determine possible causes for the somewhat poor results. Metallurgical studies revealed microscopic foreign substances at both fatigue crack locations. Oxygen rich alpha segregation was suspected; however, the inclusions were examined by electron probe microanalyzer and were found to be in excess of 80% iron. The largest inclusion found was approximately 0.008 inch thick and .070 inch long. Numerous smaller iron rich inclusions were noted. The inclusion pattern indicated evidence of having been broken up and scattered in the forging process. Since fatigue cracks were found propagating away from the iron-rich inclusions it was assumed that their presence contributed to the lower fatigue life in the Ti-6Al-4V part (see Figure 72). Longitudinal tensile specimens were cut from the upper flange and web areas of the failed Ti-6Al-4V part. The following properties were obtained and correspond very closely to the tensile properties obtained in the material tests.

Specimen Location	Ultimate Tensile Strength - ksi	0.2% Yield Strength - ksi	% Elongation
Flange	149	138	10
	151	139	14
	152	140	13
Web	146	135	12
	148	137	12
	146	134	12

The IMI 679 and Ti-6Al-4V test results can be compared to the values previously obtained (Ref. 1) on Ti-6Al-6V-2Sn, Ti-13V-11Cr-3Al and 4340 steel parts which were as follows:

Alloy	Part Weight	Fatigue Life Cycles
Ti-6Al-6V-2Sn	8.72	149,960
Ti-13V-11Cr-3Al	9.22	24,870
4340 Steel (180-200 ksi H.T.)	14.58	288,750

These results indicate that IMI 679 and Ti-6Al-4V were superior to the other two titanium alloys in fatigue performance. An increase in fatigue life was expected in Ti-6Al-4V and IMI 679 since parts made from these lower strength alloys had slightly increased local section sizes which decreased local stresses during fatigue loadings.

The IMI 679 fatigue life very nearly approximated that of the steel part and is considered outstanding for several reasons. First the IMI 679 part was 31% lighter than the steel. Second, the IMI 679 part, like the other titanium alloy parts, was machined from very heavy sections to be representative of much larger parts, whereas the 4340 steel part was forged to final dimension of the parts. Considering these factors, the IMI 679 part is considered to show particular promise for high performance in forgings used in fatigue critical applications.

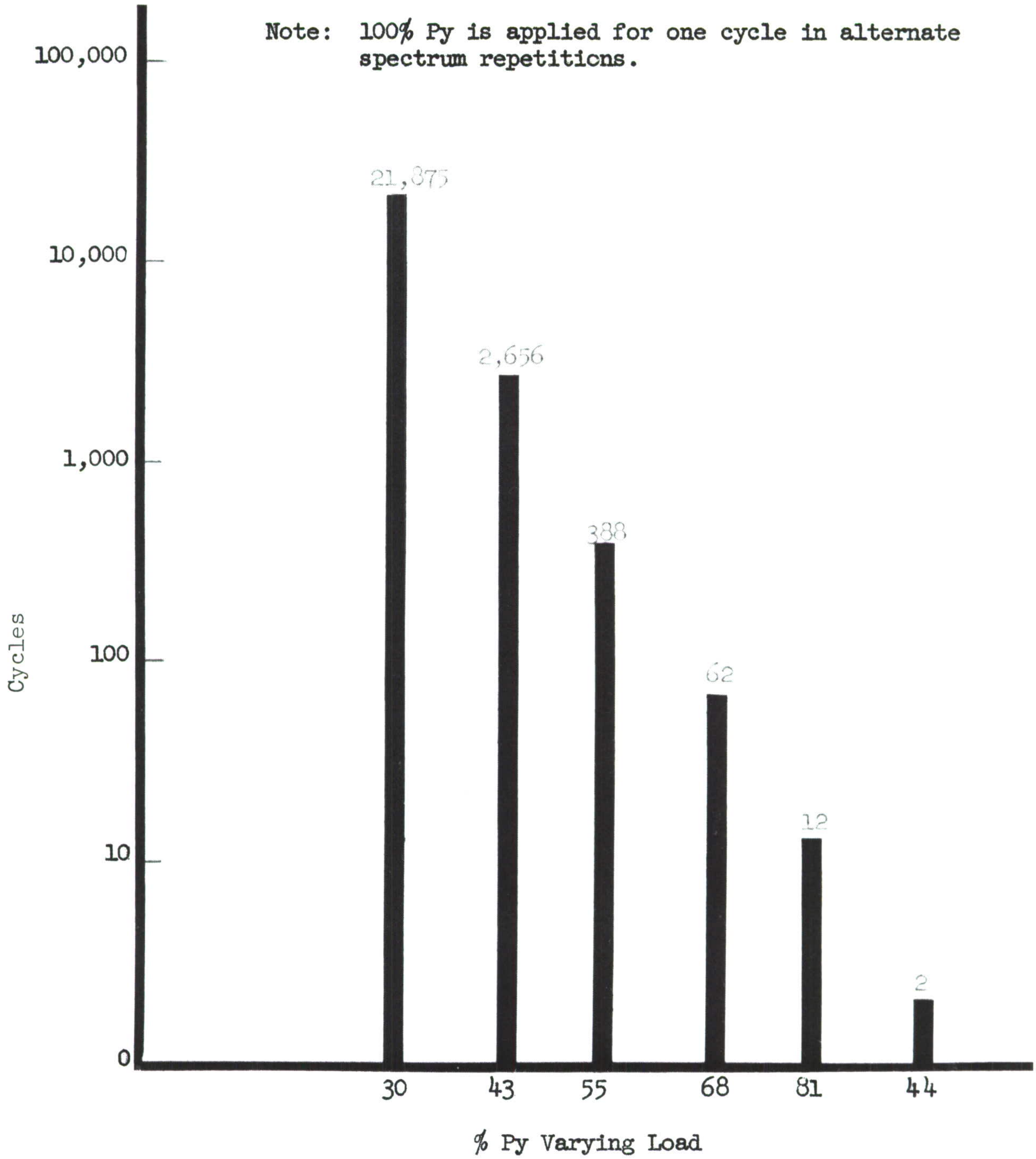
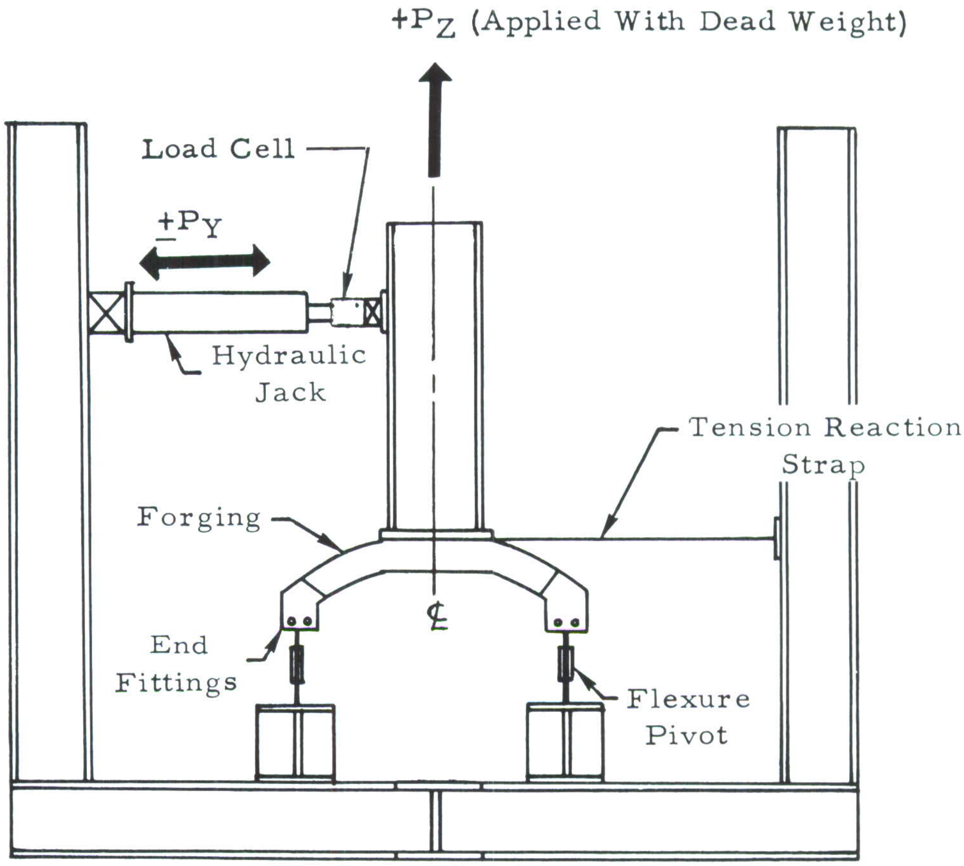


Figure 66. **Fatigue Test Loading Unit Spectrum**



Note: P_Y load applied 30 inches from top deck of forging

Figure 67. Schematic of Fatigue Test Set-up

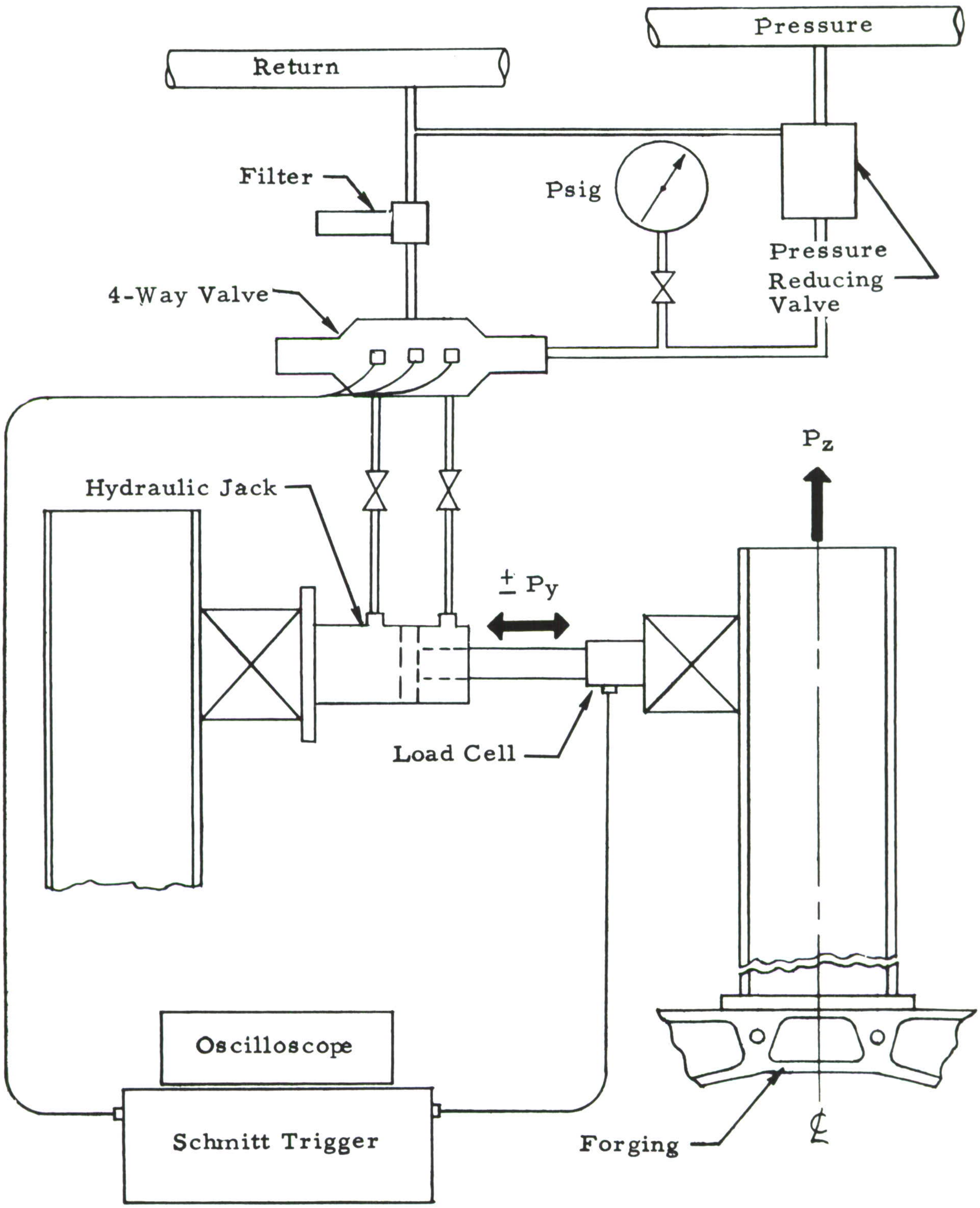


Figure 68. Fatigue Control System

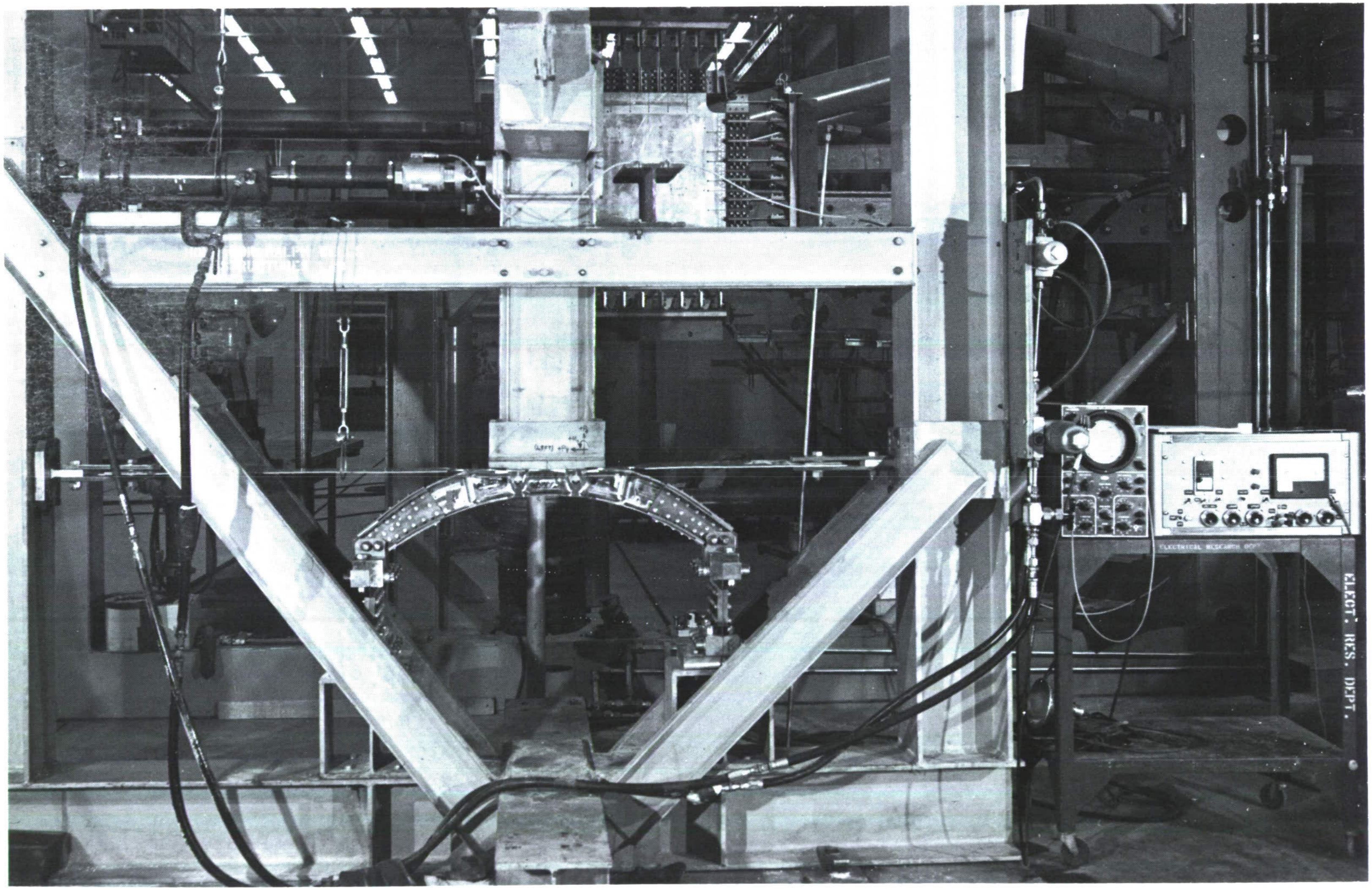


Figure 69. Fatigue Test Set-up

Figure 70. Fatigue Test Failure - IMI 679

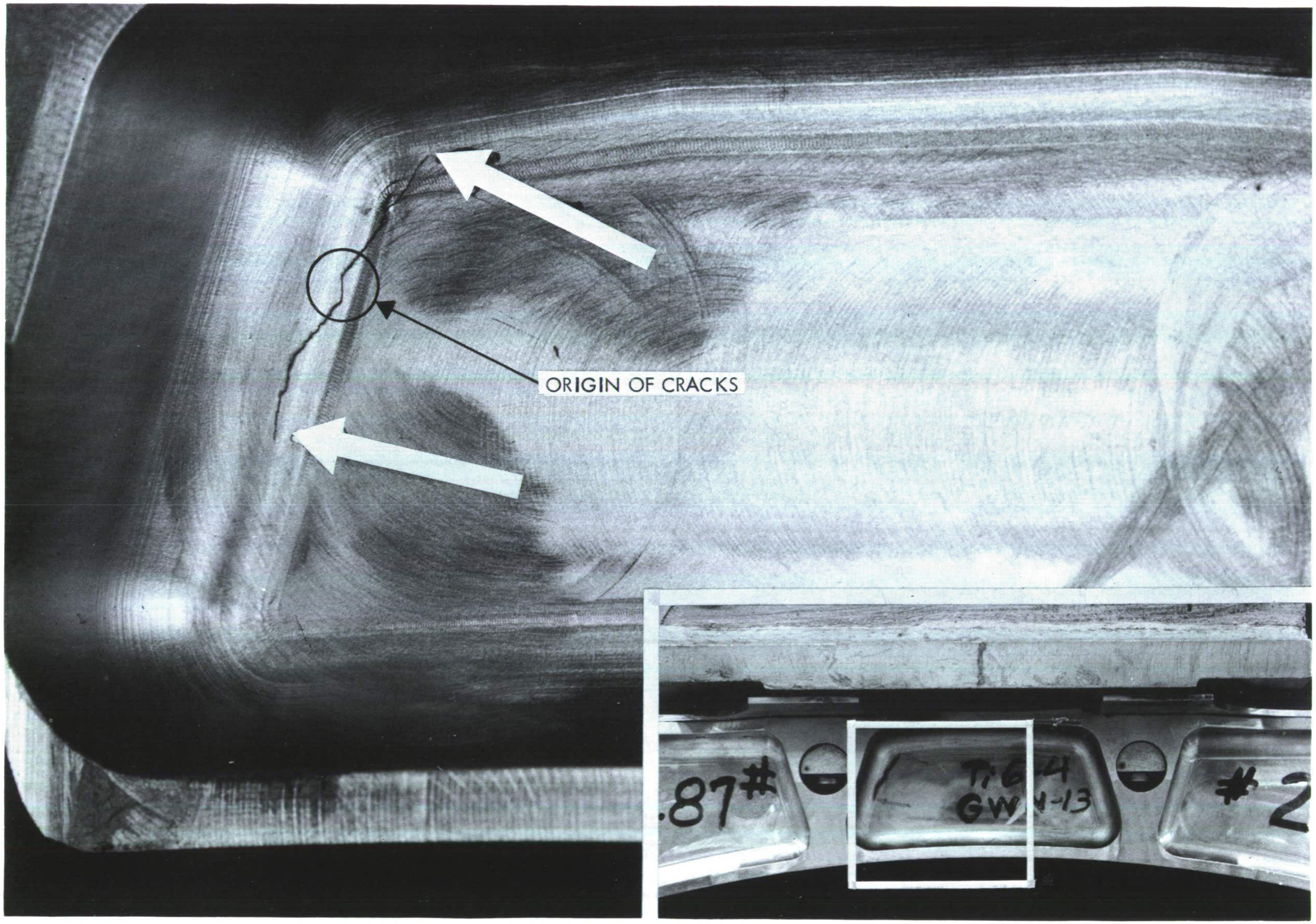


Figure 71. Fatigue Test Failure - Ti-6Al-4V

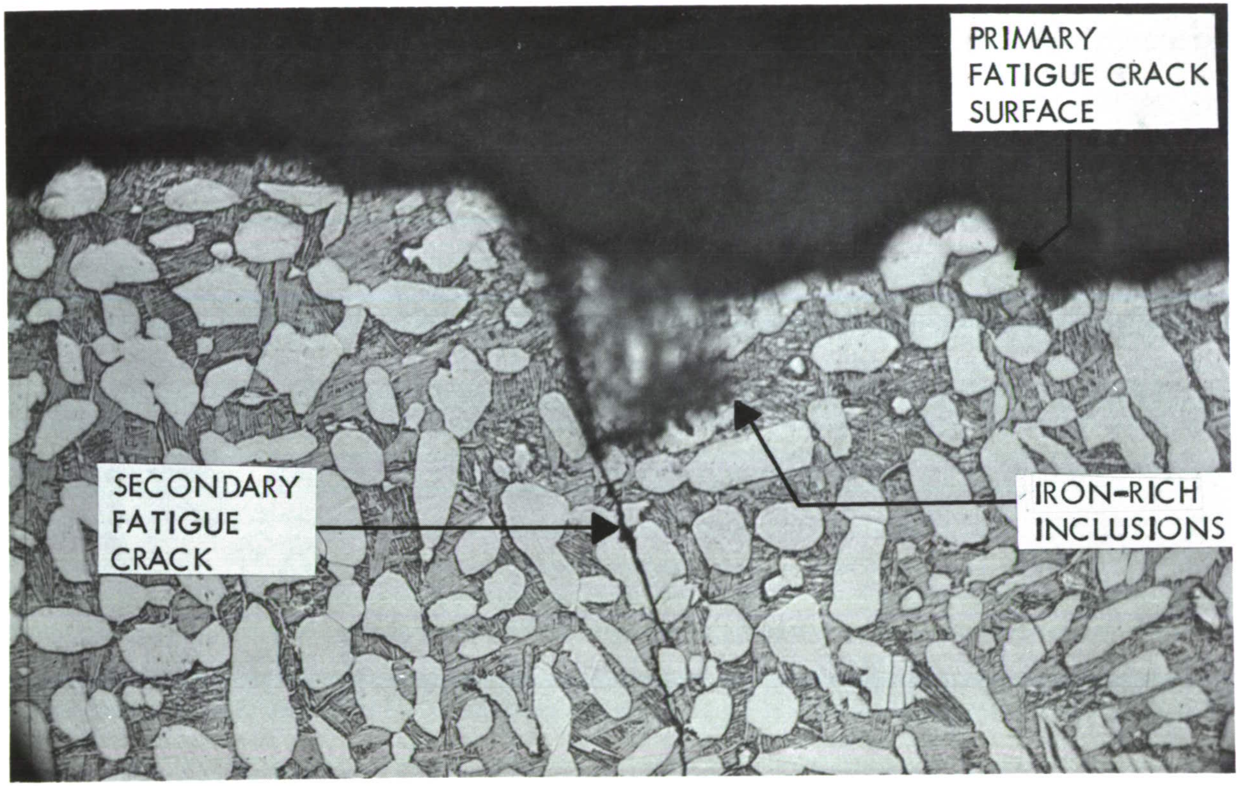


Figure 72. Ti-6Al-4V Fatigue Crack Origin (450X)

TABLE 26 FULL SCALE FATIGUE TEST RESULTS

Forging	Mean Load (Pounds)	Varying Load (Pounds)	Cycles per Unit Spectrum	Cycles: Cycles Applied per Load Level	Cycles: Total Number of Cycles Applied to Failure
Ti-6Al-4V (Part Weight = 8.87 lbs)	1,500	3,000 4,300 5,500 6,800 8,100 9,400 10,000(1)	21,875 2,656 388 62 12 2	153,094 16,219 2,328 372 72 12 3	172,100
IMI 679 (Part Weight = 10.00 lbs)	1,500	3,000 4,300 5,500 6,800 8,100 9,400 10,000(1)	21,875 2,656 388 62 12 2	244,375 29,216 4,268 682 132 22 5	278,700

(1) Load applied once each alternate unit spectrum

Section VII

CONCLUSIONS

Following are the conclusions reached upon evaluation of the complete test data.

1. The range in ultimate tensile strength of Ti-6Al-4V and IMI 679 forged stock was not significantly different from billet stock in either alloy. Elongation, reduction of area and yield strength in the IMI 679 forging were improved over those obtained in the billet stock.

2. In the Ti-6Al-4V parts the greater forging reduction received by light sections improved the ductility in these areas compared to the ductility in the forging heavy section. The IMI 679 parts did not show this effect.

3. Tensile properties in IMI 679 were highly uniform at all test locations and grain directions. The Ti-6Al-4V also showed relatively uniform properties, but all property ranges were greater than those in the IMI 679.

4. Unstressed exposure at 550°F for 1000 hours had no apparent affect on notch tensile strength, smooth tensile strength or tensile ductility in either Ti-6Al-4V or IMI 679.

5. Both Ti-6Al-4V and IMI 679 exhibited good fracture toughness at room temperature and at -110°F. Unstressed exposure at 550°F for 1000 hours did not significantly affect fracture toughness in either alloy.

6. Smooth and notched room temperature fatigue properties in IMI 679 appear to be significantly higher than those in Ti-6Al-4V. Smooth fatigue properties at 550°F were comparable in both alloys.

7. Forging of the billet stock produced an improvement in smooth fatigue properties of both alloys.

8. Full scale static and fatigue test results of Ti-6Al-4V and IMI 679 compared favorably with the previous test results on Ti-6Al-6V-2Sn, Ti-13V-11Cr-3Al and 4340 steel from Reference 1. The Ti-6Al-4V and IMI 679 static test parts both failed in a location and manner similar to that of the 4340 steel part.

9. The actual capability of Ti-6Al-4V in the full scale fatigue test was not definitely established, because the presence of iron rich inclusions probably shortened the life of the Ti-6Al-4V part. The IMI 679 fatigue results on the full scale part and test coupons indicate this alloy has potential for improved performance over other titanium alloys for fatigue critical applications.

10. Both light and heavy section forged Ti-6Al-4V showed good resistance to delayed failure in salt water. IMI 679 forged in light sections was also resistant to delayed failure in salt water, but IMI 679 forged and heat treated in heavy sections showed susceptibility to delayed failure phenomenon.

Section VIII

RECOMMENDATIONS

This program and the program described in Reference 1 evaluated and characterized a total of four different titanium alloy forgings for application in future weapons systems. Crack growth rate data was not obtained in either of these programs; however, the rate and manner of crack propagation from initial flaw size are considered essential in the evaluation of material suitability. Therefore, it is recommended that studies be conducted on these alloys to determine crack growth rates in fatigue testing in both air and salt water environments.

The British alloy IMI 679 has had only limited evaluation in the United States; in view of the outstanding fatigue properties found in this program, increased evaluation seems warranted. Recent information indicates the alloy can be quenched and tempered to higher strength levels than evaluated in this program. It is recommended that further evaluation studies be conducted to establish a greater body of basic property data and to determine possible advantages of higher strength heat treatments.

Appendix I

BILLET TEST DATA

This appendix contains data supplied by TMCA and Wyman-Gordon which are pertinent to the forging evaluation. Chemical analysis data for the two titanium alloys studied are given in Table 27. Billet processing history is shown in Table 28. Mechanical properties on full section size billet stock and upset billet stock are given in Table 29.

Data on tensile properties for all three grain directions on Ti-6Al-4V and IMI 679 billet stock are given in Tables 30 and 31. The billet material was 4 inches thick at time of heat treatment. In the case of the Ti-6Al-4V alloy, the actual forging material was machined to a maximum of 2-1/2 inches at time of heat treatment. Therefore, the Ti-6Al-4V billet properties would be expected to be somewhat lower than those obtained in the forgings. Nevertheless, good properties were obtained in the 4-inch thick slab of Ti-6Al-4V. Tensile properties of both the Ti-6Al-4V and IMI 679 are equivalent. For a similar location, properties in the longitudinal grain direction were comparable to those in one transverse grain direction in both alloys. Test specimens in the other transverse grain direction were located near the surface and had higher strengths than specimens in either of the other two directions. The Ti-6Al-4V and IMI 679 billet properties are compared graphically in Figure 73.

A transverse macrosection of Ti-6Al-4V billet stock is shown in Figure 74. Longitudinal and transverse macrosections of IMI 679 billet stock are shown in Figures 75 through 77. The IMI 679 billet macrograph shows a ring pattern which is apparently typical of this alloy. See Section IV for discussion of ring pattern.

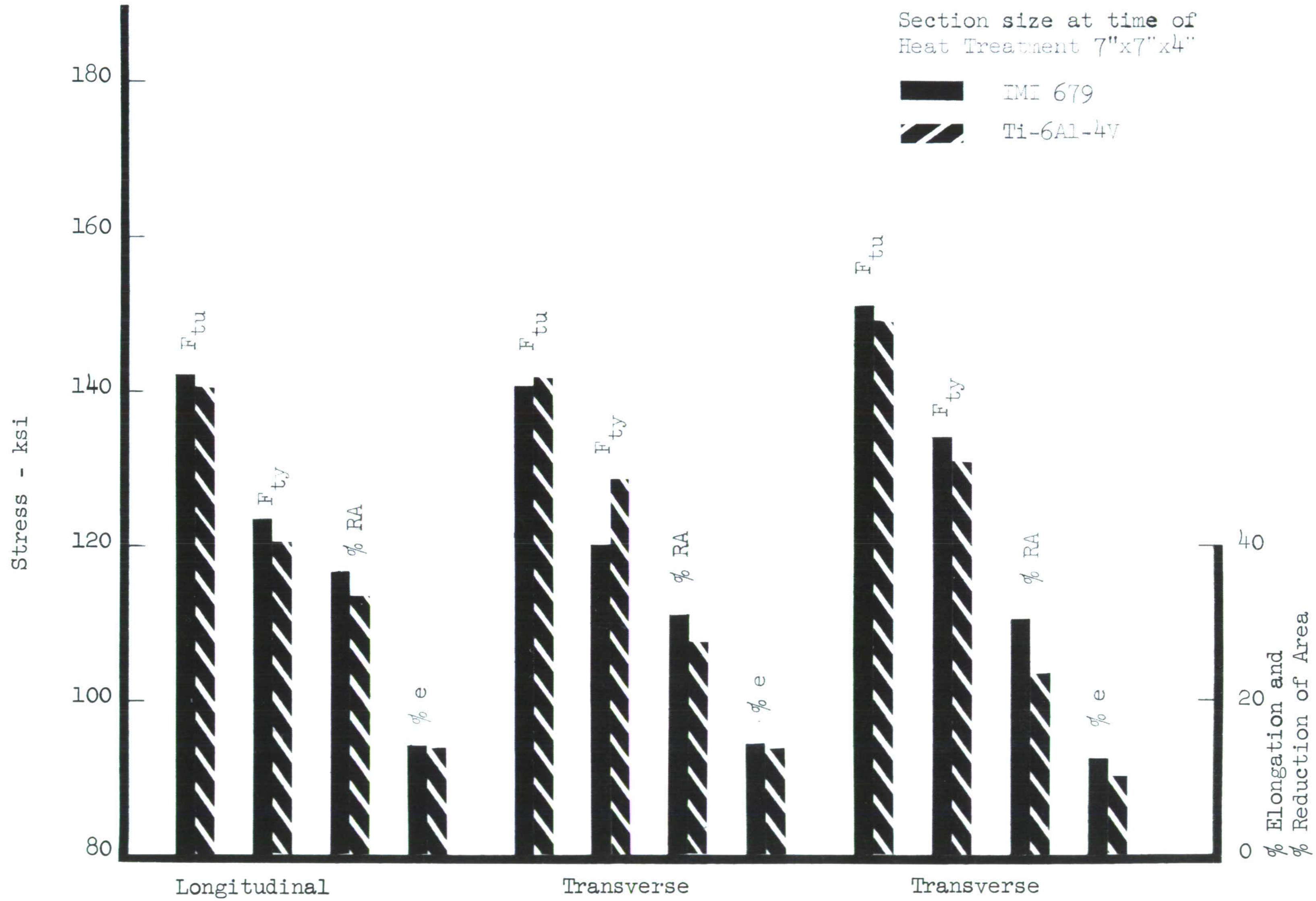


Figure 73. Comparison of IMI 679 and Ti-6Al-4V Billet Tensile Properties at Room Temperature

Figure 74. Macrosection of Ti-6Al-4V Billet Stock - Transverse

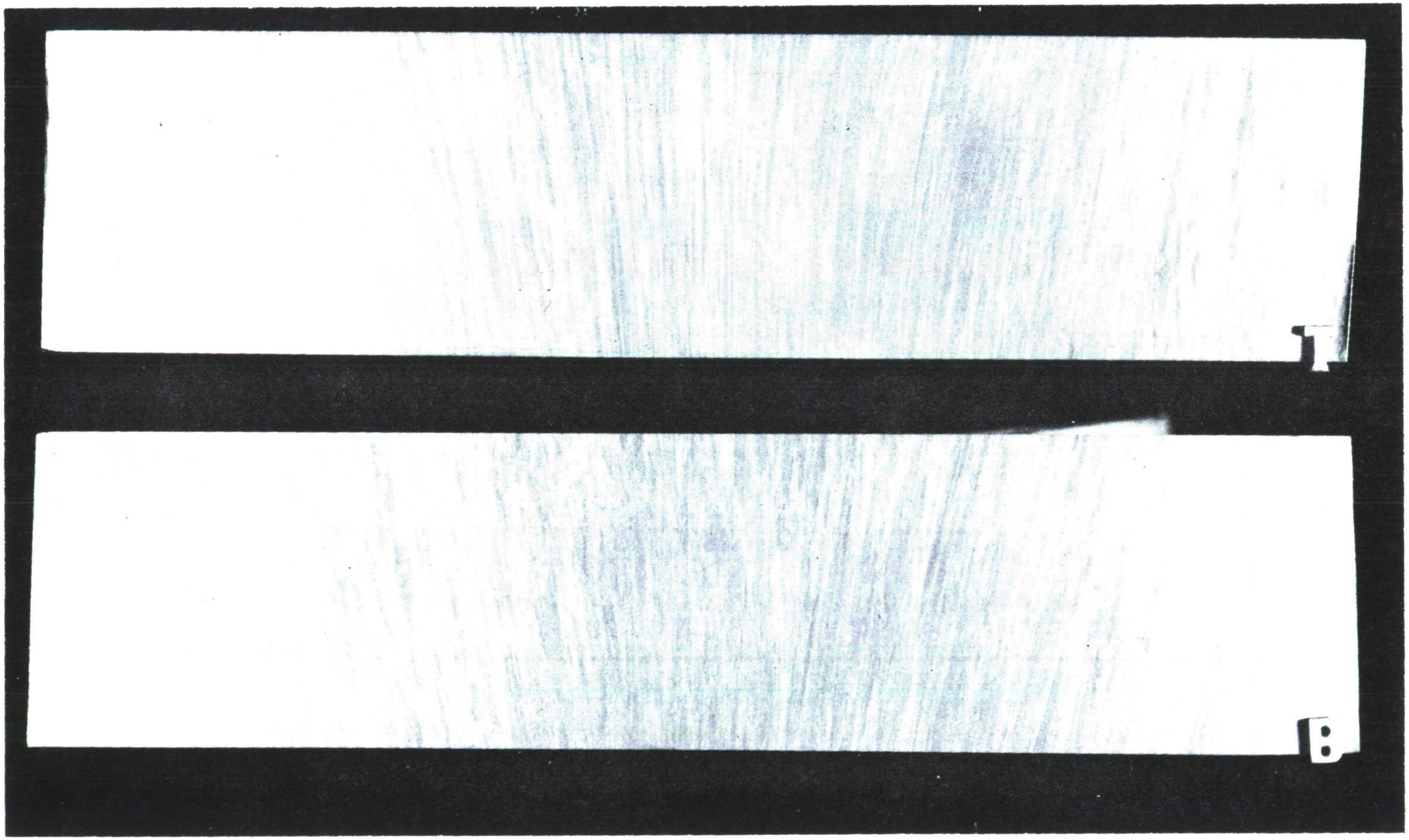


Figure 75. Macrosection of 7-Inch RCS Billet Stock IMI 679, Longitudinal Top (Upper) and Transverse Bottom (Lower)

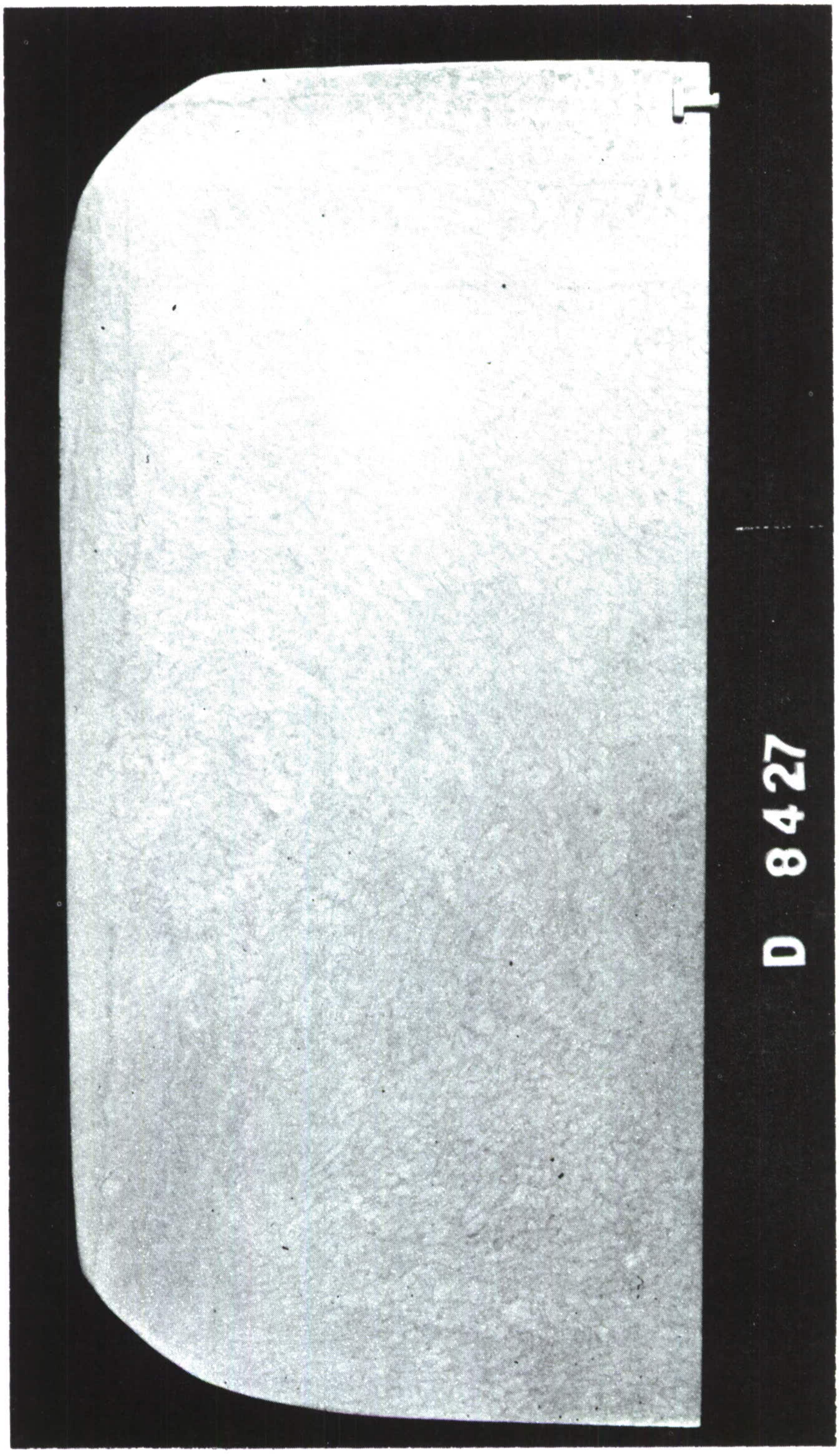


Figure 76. Macrosection of 7-Inch RCS Billet Stock IMI 679, Transverse - Top

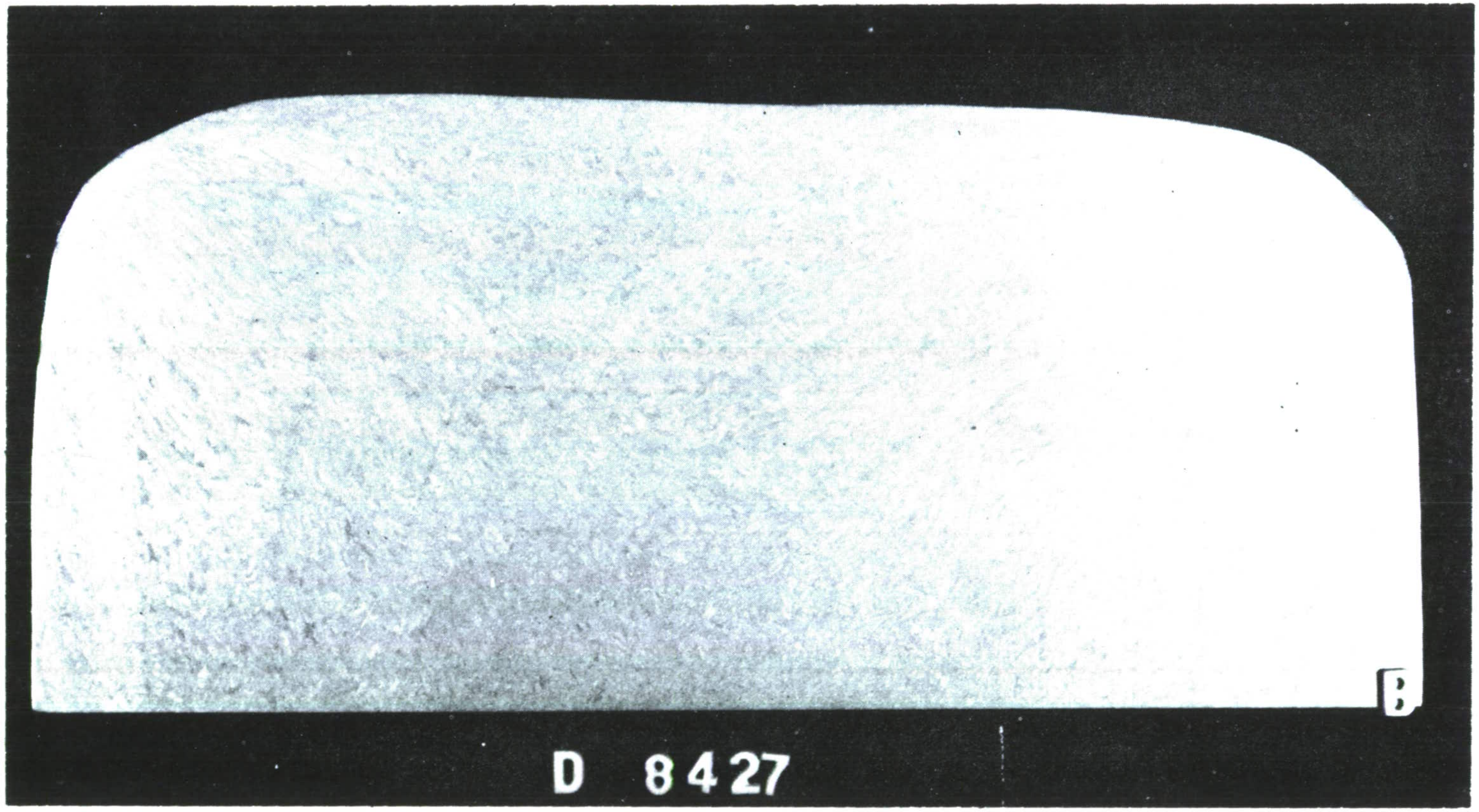


Figure 77. Macrosection of 7-Inch RCS Billet Stock IMI 679, Transverse - Bottom

TABLE 27. TMCA CHEMICAL ANALYSIS

Alloy	Heat No.	C	Fe	N	Al	V	Mo	H	Zr	Sn	O_2	Si
Ti-6Al-4V	D-7976											
	T	.026	.12	.018	6.3	4.2		.007			.17	
	M	.022	.08	.018	6.3	4.1		.009			--	
	B	.022	.08	.022	6.3	4.0		.009			.20	
IMI-679	D-8427											
	T	.022	.08	.009	2.0		.9	.005	4.9	11.1	.11	.23
	M	.022	.05	.008	2.0		1.0		4.4	11.3		.24

TABLE 28 BILLET PROCESSING HISTORY[1]

Mill History	Ti-6AL-4V	IMI 679
Heat Number	D-7976	D-8427
Ingot	28" Round	28" Round
Final Forging Operation 1200 Ton Press	12" Square to 7 3/4" Square - 1800°F	12" Square to 7 3/8" Square - 1675°F
Anneal	1300°F - 2 hrs, A.C.	1400°F - 2 hrs, A.C.
Hard Wheel Grind	30 Grit Aluminum Oxide	30 Grit Aluminum Oxide
Hand Spot Grind	46 Grit Aluminum Oxide	46 Grit Aluminum Oxide
Stress Relieve	1000°F - 2 hrs, A.C.	1000°F - 2 hrs, A.C.

(1) Data supplied by TMCA

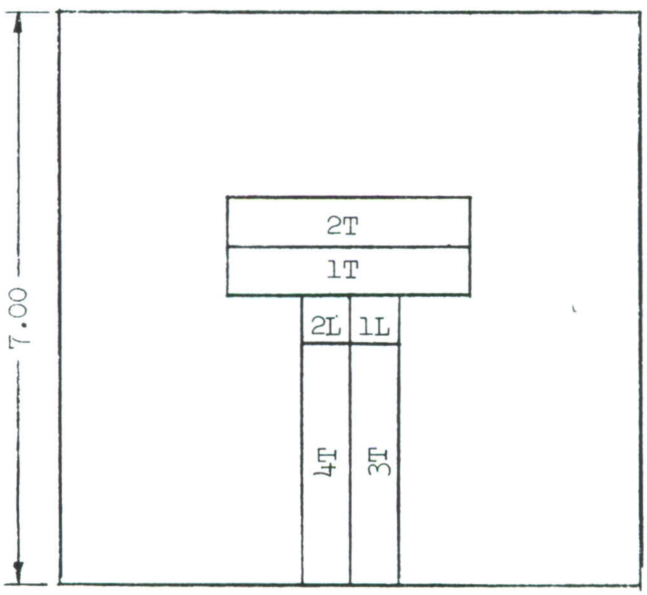
TABLE 29. TMCA MECHANICAL PROPERTIES

Alloy	Heat No.	Heat Treatment	Test No.	Tensile Strength ksi	Yield Strength ksi	Elong. % inch	R.A. %	Hardness Rc
Ti-6Al-4V	D-7976	Upset 2" to 3/4" at 1750°F Annealed 2 hrs. at 1300°F	(top) Rad.	144.8	133.9	18.0	38.2	31.5
			Tang.	149.2	138.9	18.0	34.9	30.5
			(bottom) Rad.	147.6	137.0	16.0	32.5	34.5
			Tang.	145.9	138.4	18.0	40.1	31.5
	D-7976	Solution Treated (1 hr. 1725°F W.Q.	(top) Rad.	171.1	156.2	13.0	40.6	
			Tang.	168.3	158.1	14.0	39.3	
		Lab. Aged (3 hrs) 900°F	(bottom) Rad.	167.5	157.0	13.0	31.7	
			Tang.	168.7	157.0	15.0	38.7	
IMI-679	D-8427	Upset 2" to 3/4" at 1650°F Solution Treated 1 hr. at 1650°F Aged 24 hours at 930°F	Rad.	152.6	133.9	19.0	44.9	
			Tang.	151.2	134.3	14.5	44.9	

TABLE 30. BILLET STOCK TENSILE TEST RESULTS
Ti-6Al-4V TMCA HEAT D-7976 (1)
(7 x 7 x 4 Billet)

Specimen Number	Ultimate Tensile Strength ksi	Yield Strength 0.2% ksi	Elong. % 1 in.	R.A. %
1L	143.0	127.0	13.0	32.7
2L	137.6	114.0	14.5	33.8
1T	143.4	128.4	12.5	26.6
2T	140.0	128.8	15.0	28.3
3T	150.0	132.0	10.0	21.7
4T	148.0	129.2	10.0	25.1

(1) Heat Treatment:
Solution Treated 1750°F (1 hour) W.Q.
Aged 1000 F (4 hours) A.C.

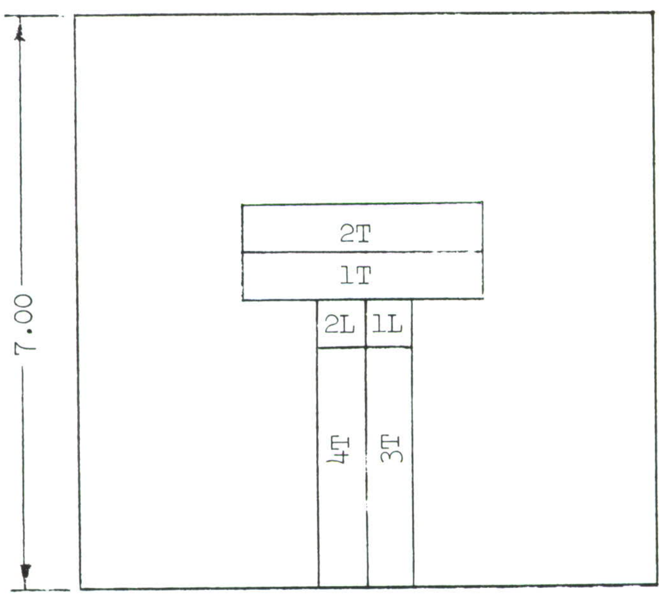


Test Locations

TABLE 31. BILLET STOCK TENSILE TEST RESULTS
Ti-IMI 679 - TMCA HEAT D-8427(1)
(7 x 7 x 4 Billet)

Specimen Number	Ultimate Tensile Strength ksi	Yield Strength 0.2% ksi	Elong. % 1 in.	R.A. %
1L	144.0	125.6	13.5	35.7
1T	139.0	118.0	14.0	33.8
2L	140.0	121.8	15.0	38.2
2T	142.0	122.0	11.5	29.9
3T	152.0	134.0	15.0	31.1
4T	150.0	133.8	10.0	29.9

(1) Heat Treatment:
Solution Treated 1650°F (1 hour) Fan Cool
Aged 930°F (24 hours) Air Cool



Test Locations

Appendix II

FORGING PROCEDURES

Section III presented some of the basic details related to production of the closed die titanium alloy forgings. Additional information pertaining to the forging procedures is presented in this Appendix.

The initial billet crossworking procedure is depicted in Figure 78. The die sinking model and master for the finish die are shown in Figures 79 and 80. The bender die with a wood template in place is shown in Figure 81. Significant details related to heat up times, forging equipment, sequence of operation, etc., are given in Tables 32 and 33. As indicated in these tables all forging operations were done on press equipment. In each forging stage the dies were pre-heated to approximately 800°F. Conventional graphite lubricants were applied to the forging blanks and the dies. All procedures were identical to those used in the previous program (Ref. 1) with the exception of forging temperatures.

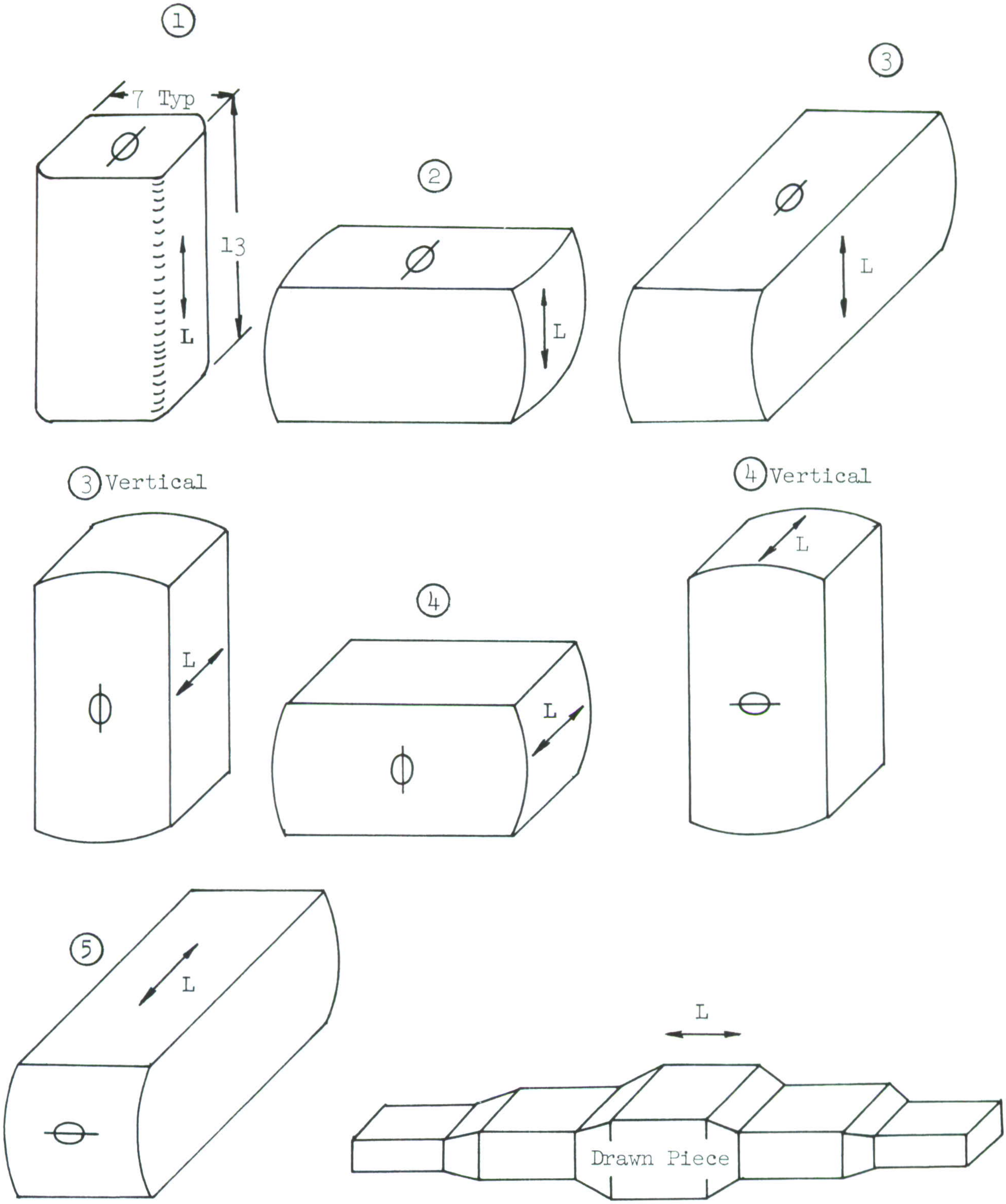


Figure 78. Initial Billet Crossworking Procedure

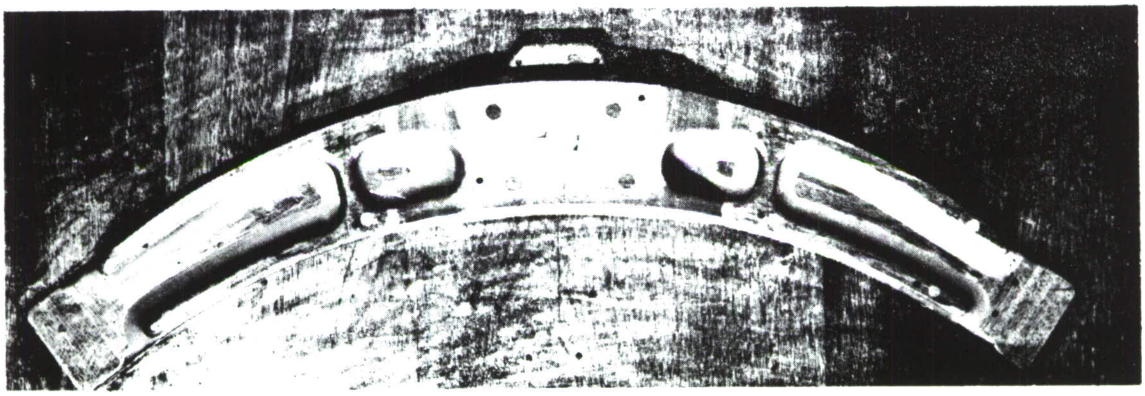


Figure 79. Die Sinking Model - Finish Die

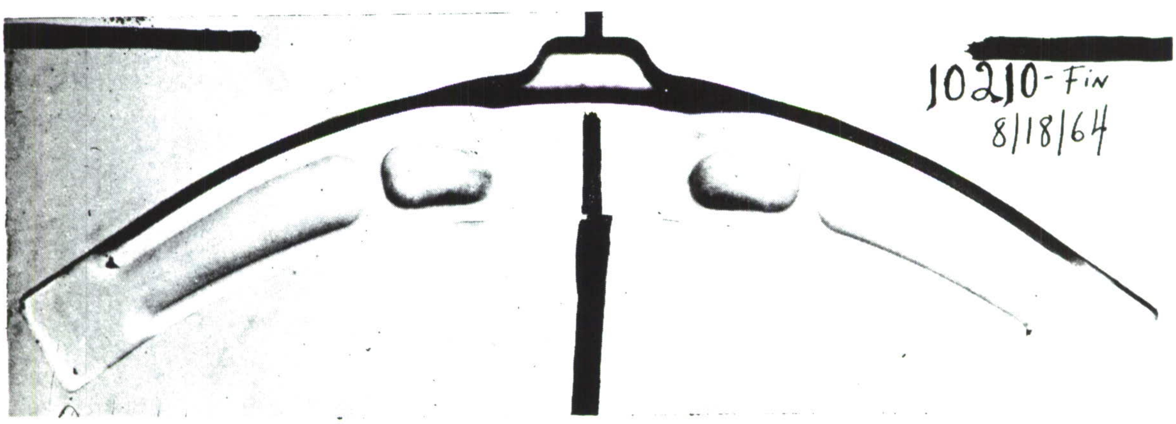


Figure 80. Die Sinking Master - Finish Die

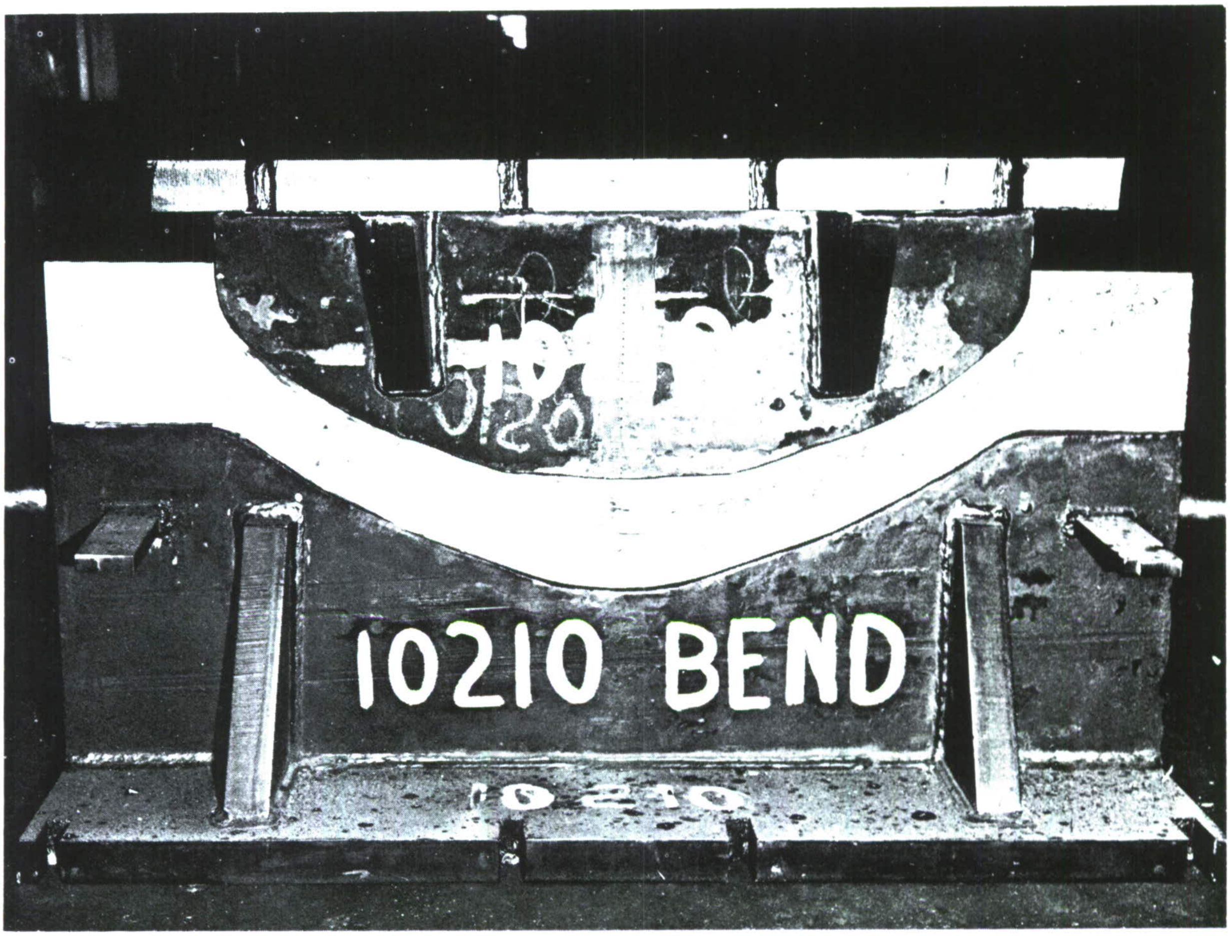


Figure 81. Bender Die with Wood Template in Place

TABLE 32. Ti-6Al-4V FORGING PROCESS DATA

Forging Number	Cut Weight lbs.	Forge Operations	Press Equipment tons	Heat Cycle hrs.	Furnace Temp. °F	Temperature of Forging, °F		
						Out Furnace	On Dies	Off Dies
1	106	Draw	1,500	6	1800	1725	1665	1450
2	106-1/2					1720	1650	1450
3	107					1725	1665	1450
4	108					1725	1660	1450
1	---	Bend	600	2-1/2	1800	1730	1670	1500
2	---					1725	1665	1540
3	---					1730	1670	1500
4	---					1740	1680	1500
1	---	1st Finish	18,000	2-1/2	1775	1735	1665	----
2	---					1725	1660	----
3	---					1720	1600	----
4	---					1725	1670	----
1	---	2nd Finish	18,000	1/2	1775	1725	1660	----
2	---					1730	1660	----
3	---					1725	1670	----
4	---					1720	1670	----

All cooling was in air

TABLE 33. Ti IMI 679 FORGING PROCESS DATA

Forging Number	Cut Weight lbs.	Forge Operation	Press Equipment tons	Heat Cycle hrs.	Furnace Temp. °F	Temperature of Forging, °F		
						Out Furnace	On Dies	Off Dies
1	108	Draw	1,500	5	1675	1600	1550	1450
2	109			5		1610	1540	
3	109			7-1/2		1600	1530	
4	111			7-1/2		1620	1550	
1	---	Bend	600	3	1675	1630	1555	1500
2	---					1620	1540	1485
3	---					1625	[illegible]	1495
4	---					1630	1520	1500
1	---	1st Finish	18,000	2-1/2	1675	1560	1470	1400
2	---					1580	1490	
3	---					1580	1500	
4	---					1560	1470	
1	---	2nd Finish	35,000	2-1/2	1675	1610	1545	---
2	---					1620	1555	---
3	---					1610	1550	---
4						1615	1545	---

All cooling was in air

Appendix III

MATERIAL PROPERTY TEST PROCEDURES

The test procedures, temperatures, type of tests, and specimen locations used in this program were identical to those of Reference (1) with the exception of the bearing specimen which was reduced from 1/8 inch thickness to 1/16 inch thickness. This permitted comparison between the alloys in the current contract and those in the previous study.

A discription of the test procedures and specimen configurations used in this program is presented below.

SMOOTH TENSILE TESTS

The specimen used in the smooth tensile test is shown in Figure 82. Tests were conducted in accordance with the requirements of FED-STD-151 using a strain rate of 0.005 in./in./min. Full length autographic stress-strain curves were obtained by the use of a microformer type extensometer.

COMPRESSION TESTS

The specimen used in the compression test is shown in Figure 83. Tests were conducted using a strain-rate of 0.005 in./in./min. Autographic stress-strain curves were obtained by the use of an extensometer.

SHEAR TESTS

The specimen used in the shear test is shown in Figure 84. Double shear type tests were conducted using standard shear fixtures. The load was applied at a constant head travel rate of 0.1 inch/minute.

BEARING TESTS

The specimen used in the bearing test is shown in Figure 85. The bearing hole was drilled and reamed to within one-thousandth of the diameter of the hardened steel loading pin. The test apparatus incorporated a deflection measuring system to obtain bearing yield values. Loads were applied at a constant deformation rate of 0.006 inch per minute through the yield point ($e/D = 2.0$).

NOTCH TENSILE TESTS

The specimen used in the notched tensile test is shown in Figure 86. This specimen incorporates a stress concentration factor (K_t) of 3.9. The loading equipment and strain rate are identical to those employed in the smooth tensile tests.

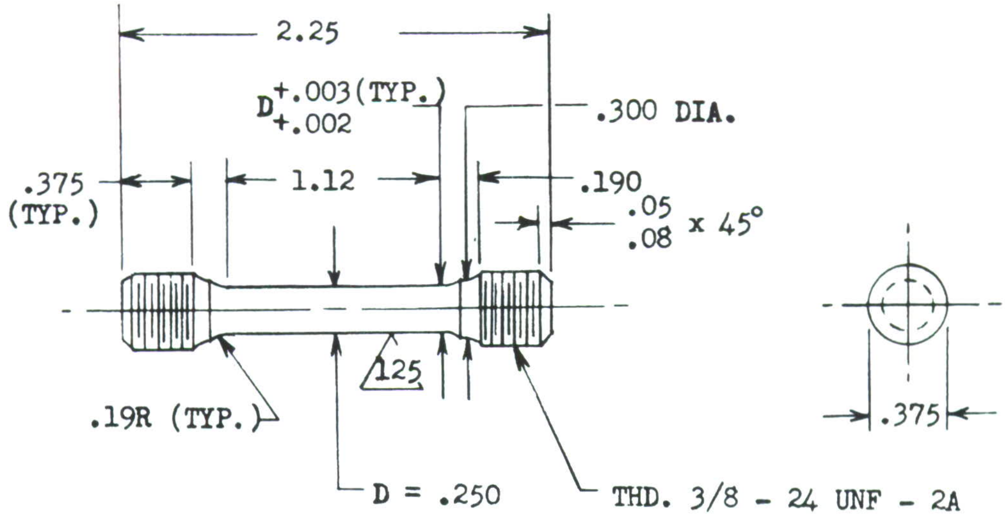


Figure 82. Smooth Tensile Specimen

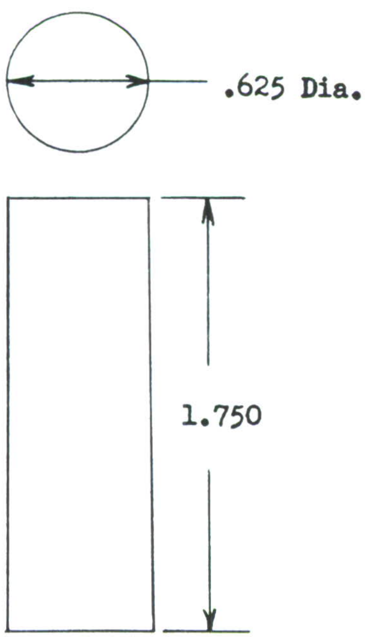


Figure 83.
Compression Specimen

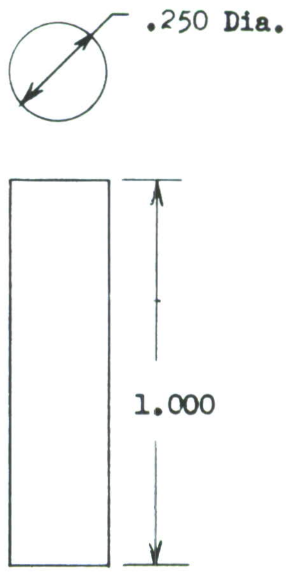


Figure 84.
Shear Specimen

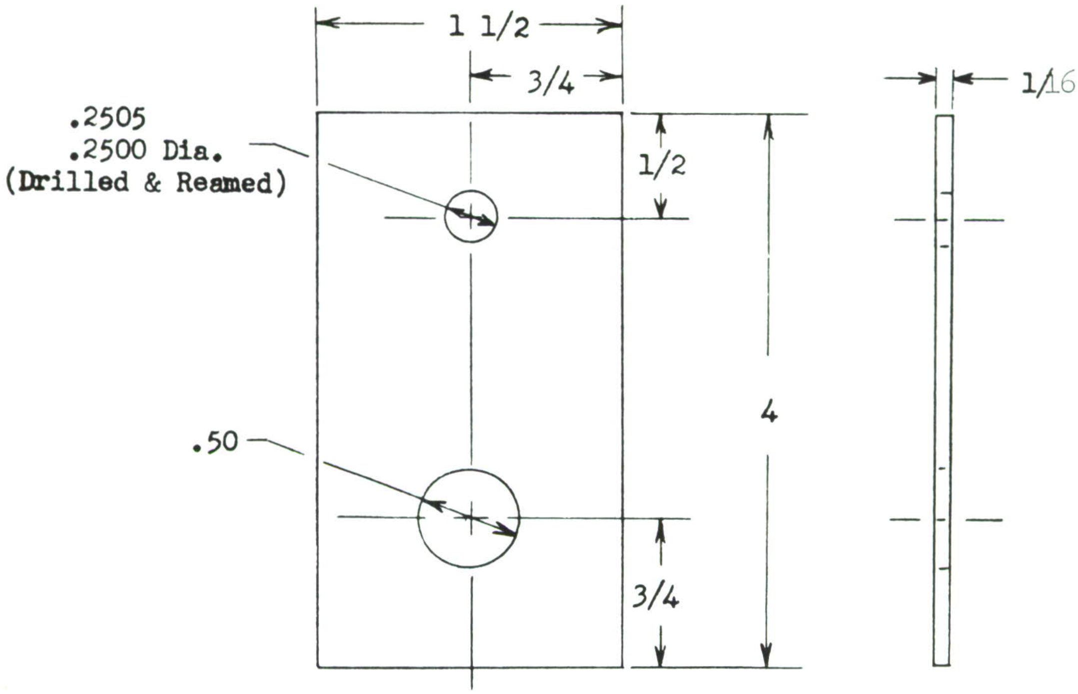


Figure 85 Bearing Specimen

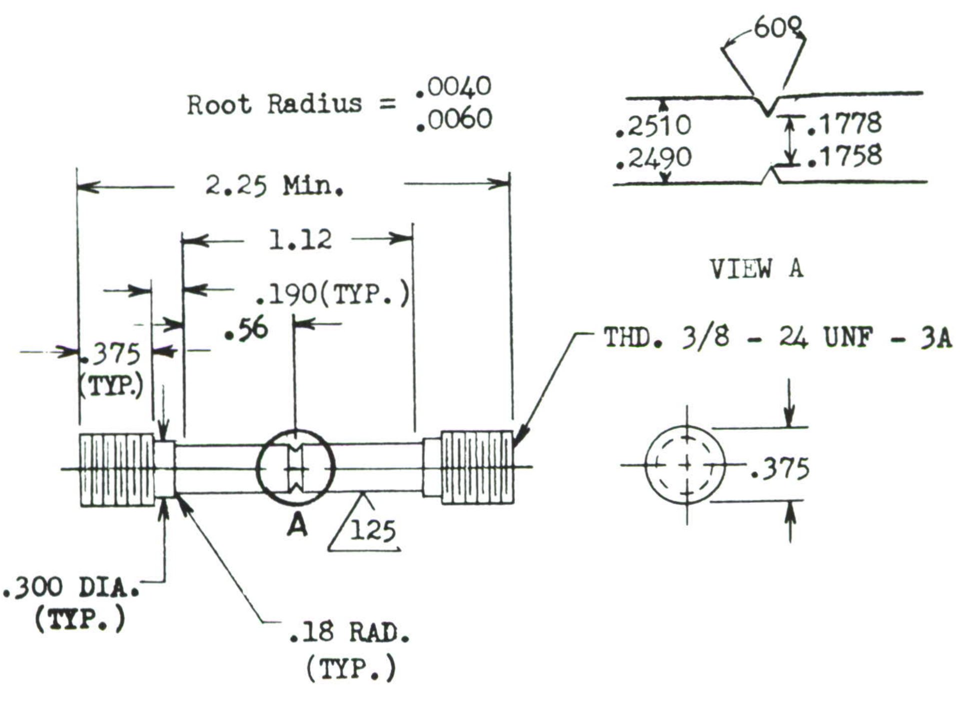


Figure 86. Notch Tensile Specimen ($K_t = 3.9$)

FATIGUE TESTS

The specimens used in the fatigue tests are shown in Figures 87 and 88. Both notched and smooth fatigue specimens were axially loaded in tension-tension at several stress levels using a stress ratio of R = 0.1. The notched fatigue specimen incorporates a stress concentration factor (K_t) of 3.0.

FATIGUE-CRACKED ROUND BAR FRACTURE TOUGHNESS

The fracture toughness test specimen configuration used in this program is shown in Figure 89.

The specimen was pressed into a ball bearing block assembly and then was chucked into the head of the lathe and centered. A split sleeve was inserted in the lathe chuck for accepting the specimen and to prevent galling by the chuck jaws.

The loading assembly consisted of a clevis, load transducer and universal joint. The loading clevis was pin connected to the bearing block assembly, and the base of the universal joint was rigidly attached to the bed of the lathe. Specimen cantilever bending was accomplished by applying torque to the bolt attaching the loading clevis to the transducer. Transducer loads were monitored by means of an SR-4 strain indicator.

A typical cantilever bending load of 450 lb was applied to the specimen after maximum rotational speed of the lathe was achieved. A direct drive, 20-inch LeBlond lathe was used at its maximum setting of 800 rpm. Lathe rotational speed was checked by the use of a strobotac and automatic frequency counter.

After crack initiation, the specimens were tensile tested by applying the load at a constant rate of 5000 lb/min. until failure.

Plane strain fracture toughness (K_{1c}) was calculated from the following formula:

$$K_{1c}^{2} = \frac{EG_{1c}}{(1-\nu^{2})} = \frac{1.63P^{2}D}{d^{4}}\left[0.172 - 0.8\left(\frac{d}{D} - 0.65\right)^{2}\right]$$

where:

K_{1c} = Critical stress intensity factor, psi$\sqrt{in}$

E = Elastic modulus, psi

G_{1c} = Critical crack-extension force, $\frac{in.\text{-}lb}{in.^{2}}$

ν = Poisson's ratio

P = Load at fracture, lb

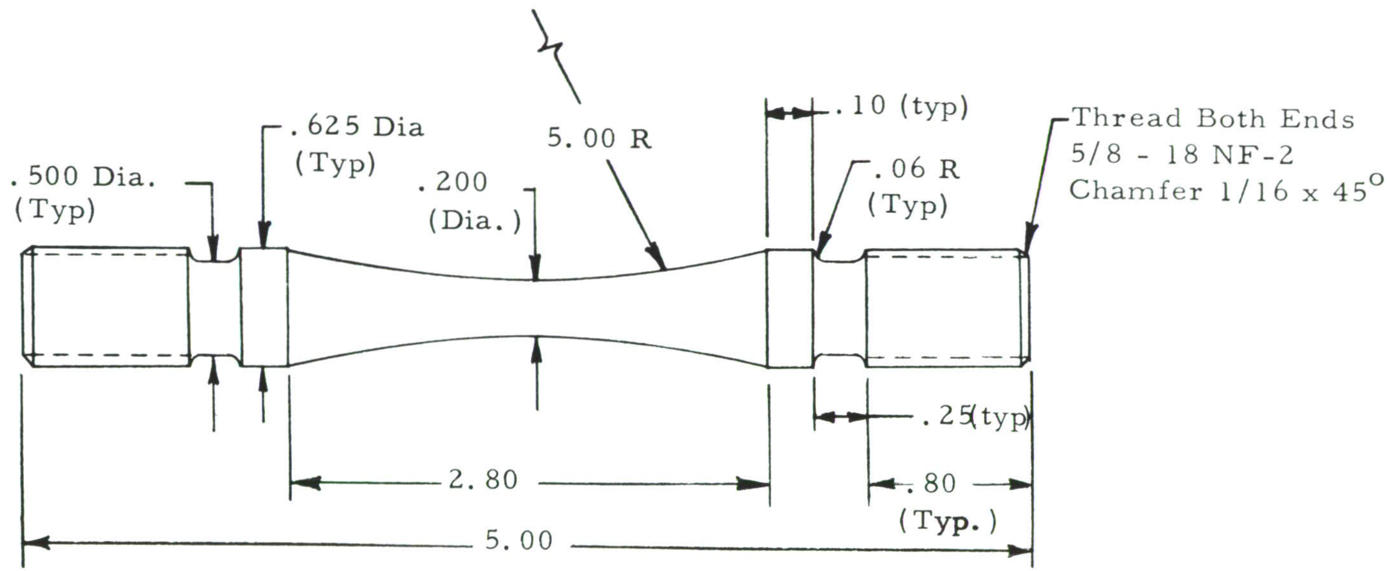


Figure 87. Smooth Fatigue Specimen

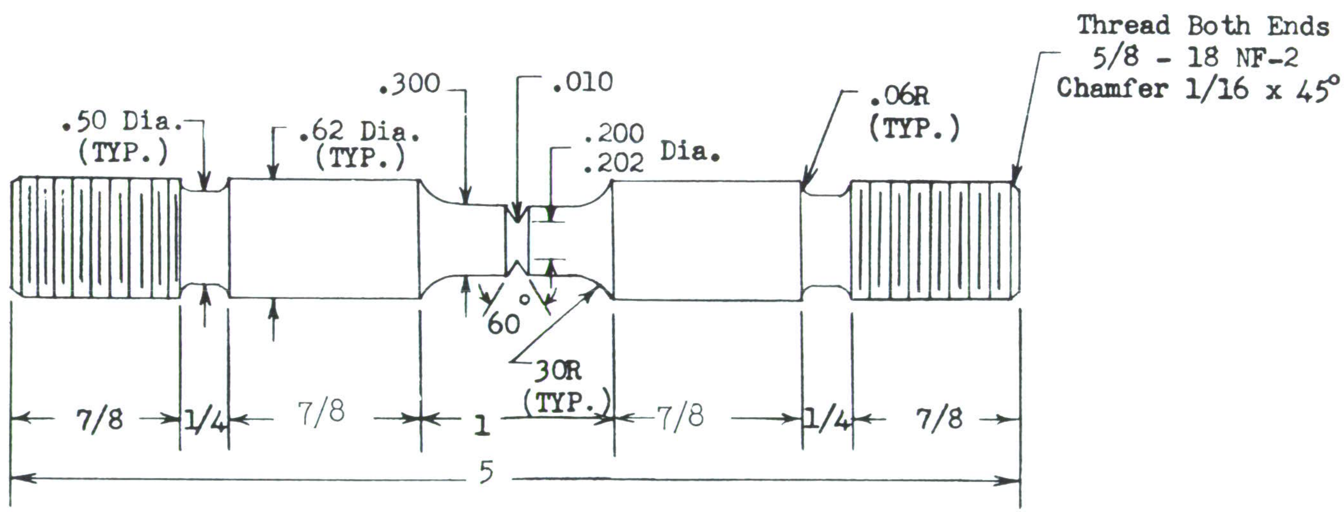


Figure 88. Notch Fatigue Specimen ($K_t = 3.0$)

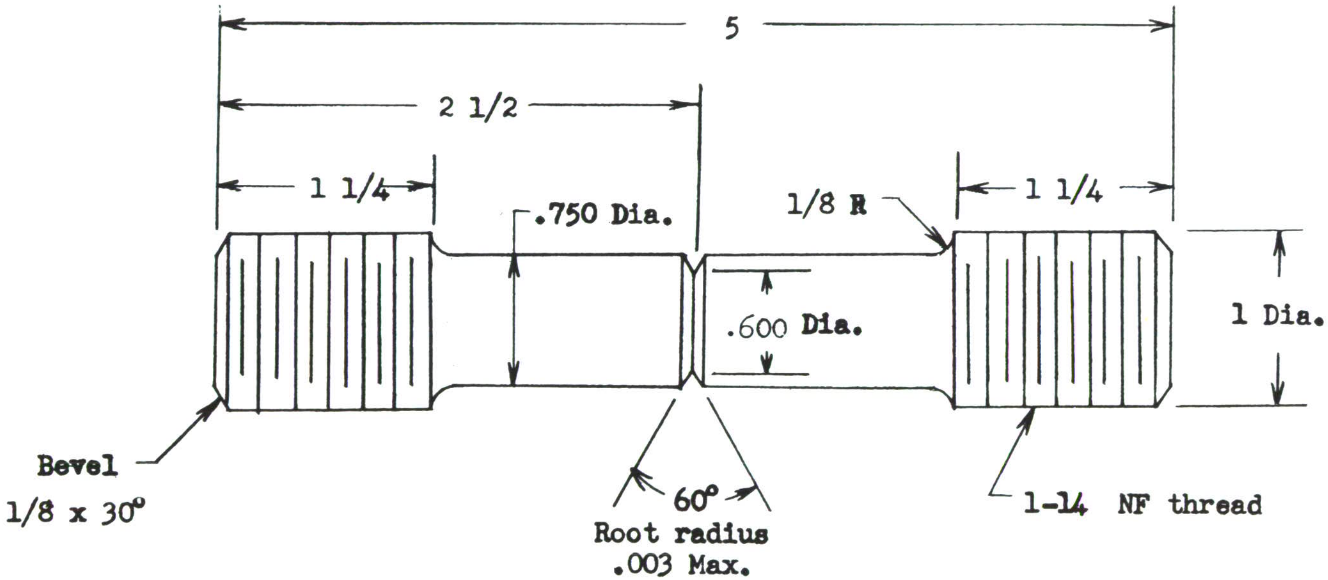


Figure 89. Plane-Strain Fracture Toughness Test Specimen

do = Minimum diameter of fatigue crack at the root of the notch, in.

D = Major diameter of specimen, in.

$$d = do - \frac{(K_{1c})^2}{3\pi \sigma_{ys}^2}$$

σ_{ys} = Yield strength of the material at 0.2 percent offset, psi

TENSION AND COMPRESSION MODULUS OF ELASTICITY

The tension and compression specimens used for the modulus determination are shown in Figures 82 and 83. All tests were conducted at room temperature in a 120,000 lbs Baldwin Universal test machine incorporating a Tuckerman optical strain measuring system. Two gages were attached to opposite sides of each specimen and strain readings were taken for six constant load increments to a maximum stress of approximately 40 ksi. The strain readings for each gage were plotted as load-strain curves and the slope of a straight line through the points was calculated. The average of the slope values for the two gages was used to calculate the modulus for that test cycle.

BEND BAR FRACTURE TOUGHNESS AND DELAYED FAILURE TESTS

The specimen used for the fracture toughness and delayed failure resistance tests is shown in Figure 90. This specimen is a four-point loaded constant moment bend specimen containing a fatigue crack approximately 0.1 inch deep. A fracture toughness value was established in air by loading the specimen to failure at a loading rate corresponding to a nominal elastic strain rate of 0.005 in./in./min. in universal test machines. An autographic load-deflection curve was obtained for each specimen utilizing a Model PD-IM deflectometer. The plane strain fracture toughness (K_{1c}) values were calculated using the following formula:

$$K_{1c}^2 = \frac{P^2 L^2}{(1-\nu^2) B^2 W^3} \left[34.7 \left(\frac{a}{W}\right) - 55.2 \left(\frac{a}{W}\right)^2 + 196 \left(\frac{a}{W}\right)^3\right]$$

where

ν = Poisson's Ratio

P = Load at point of initial crack instability, lbs.

B = Specimen thickness, inch

W = Specimen width, inch

L = Moment arm length, inch

a = Crack depth, inch

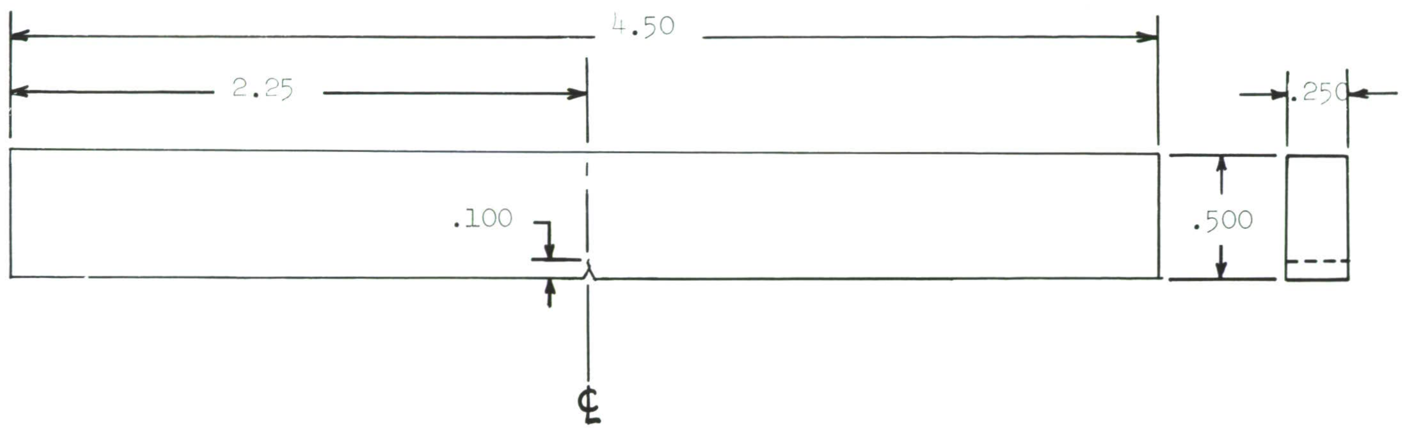


Figure 90. Fatigue-Cracked Bend Specimen

The delayed failure tests were conducted by immersing the fatigue precracked area of the specimen in a 3-1/2 percent NaCl salt water solution and then loading the specimen to an arbitrary percent of the load obtained in the air environment fracture toughness tests. This load was sustained on the specimen until failure occurred or a time period of 60 minutes elapsed with no indication of failure. If the specimen failed, the time period to failure was recorded and a second specimen was tested at a lower sustained load. If the specimen did not exhibit evidence of failure during the 60 minute period, the load was increased until failure occurred and a second specimen was tested at a higher sustained load. This testing procedure was continued until the threshold sustained load below which delayed failure did not occur and above which delayed failure did occur was defined. The threshold sustained loads were converted to a parameter, designated as the K_{li} parameter in the equation discussed above, except that the sustained load was used in the equation instead of the load at which initial crack instability occurred.

TEST TEMPERATURES

The elevated temperature and reduced temperature tests were monitored by thermocouples and controlled to within $\pm 5^{\circ}F$. The elevated temperature tests were performed in a circulating air furnace. The reduced temperature tests were performed in a cold box employing CO_2 as a coolant.

Appendix IV

FORGING SPECIFICATION

A forging specification was prepared in conformance with the Work Statement of Contract AF33(615)-2690. The specification is presented in this Appendix and is intended for use in procurement of high strength titanium alloy forgings. This specification contains the applicable requirements of the proposed MIL-T-9047D which covers annealed bars, forgings and forging stock of titanium and titanium alloys. The essential difference in the specifications is that this specification covers heat treated material. The minimum mechanical property values given conform to those established by the titanium producers.

SPECIFICATION FOR

TITANIUM-ALLOY FORGINGS, AND FORGING STOCK

1. SCOPE

1.1 Scope. This specification covers titanium alloy forgings, and forging stock, in the heat treated and aged condition.

1.2 Classification. Material shall be of the following types as specified (see 6.):

Type I Ti-6Al-4V

Type II IMI 679

2. APPLICABLE DOCUMENTS

2.1 The following standards, of the issue in effect on date of invitation for bids or request for proposal, form a part of this specification to the extent specified herein:

STANDARDS

Federal

Fed. Test Method Std. No. 151	Metals; Test Methods
Fed. Std. No. 184	Identification Marking of Aluminum, Magnesium and Titanium

Military

MIL-STD-129	Marking for Shipment and Storage
MIL-STD-163	Preparation of Steel Products for Domestic Shipment (Storage) and Overseas Shipment

3. REQUIREMENTS

3.1 Materials

3.1.1 Condition. The forgings and forging stock shall be produced by the double melt consumable electrode method and shall be hot worked, heat treated and descaled. Sufficient working shall be applied to insure that a thoroughly wrought metallurgical structure is obtained.

3.1.2 Quality. Forgings and forging stock materials shall be of a satisfactory quality when inspected by a method acceptable to the Government that will disclose defects as specified under 3.7. Forgings shall be free of embrittled surfaces.

3.2 Chemical Composition. The chemical composition as determined by heat analysis shall be as specified in table I.

TABLE I

CHEMICAL COMPOSITION, PERCENT BY WEIGHT

Element	Type I	Type II
Aluminum	5.50 - 6.75	2.00 - 2.50
Vanadium	3.50 - 4.50	
Tin		10.50 - 11.50
Zirconium		4.00 - 6.00
Molybdenum		0.80 - 1.20
Silicon		0.15 - 0.27
Iron	0.30 max	0.120 max
Carbon	0.10 max	0.040 max
Nitrogen	0.05 max	0.040 max
Oxygen	0.20 max	0.150 max
Hydrogen	0.125 max	0.008 max
Other Elements (total)		0.040 max
Titanium	Remainder	Remainder

3.3 Heat Treatment. Forgings supplied to this specification shall be heat treated as shown in Table II.

3.3.1 Specific aging times for Type I and Type II forgings shall be determined for each heat and forging lot. Forged material representative of the forgings shall be used to establish the aging time required to obtain the properties specified in Table III. Forgings shall be aged for the time selected and the corresponding test data shall be reported.

3.4 Mechanical Properties. After heat treatment as specified in item 3.3, mechanical properties shall be as specified in Table III.

3.5 Dimensions. The dimensions and shape shall be as specified by the procuring activity.

3.5.1 Tolerances. Dimensional tolerances for forgings and forging stock shall be as specified by the procuring activity.

TABLE II

HEAT TREATMENT

Material	Heat Treatment	
Type I	Solution Treatment (1)	1725°F - 1750°F for 1 hr., within 6 seconds water quench
	Age (1)	975°F - 1025°F for 4 hrs., Air Cool
Type II	Solution Treatment (1)	1625°F - 1675°F for 1 hr., Fan Cool
	Age (1)	900°F - 950°F for 24 hrs., Air Cool

(1) Any temperature within the range shown may be selected, however, the temperature selected must be held to ±25°F for the solution treatment and ±10°F for the aging treatment.

3.6 Identification of Product. Forgings and forging stock shall be marked in accordance with Fed. Std. No. 184. In addition, each forging and forging stock shall be marked with the heat, type and composition.

3.7 Workmanship. Material shall be uniform in quality and condition, clean, sound, and free from defects detrimental to fabrication or to performance of parts.

3.7.1 Rejectible Defects. Material containing voids, bursts, unmelted sponge, or deleterious inclusions, alloy segregation, or excessive brittle oxide skin, as determined by visual, penetrant, radiographic, or ultrasonic inspection methods, shall be rejectible. Small and scattered inclusions may be accepted depending on their size, geometry, and location in low-stressed areas of manufactured parts. Standards must be mutually agreed upon between producer and customer.

4. QUALITY ASSURANCE PROVISIONS

4.1 Responsibility for Inspection. Unless otherwise specified in the contract or purchase order, the supplier is responsible for the performance of all inspection requirements as specified herein. Except as otherwise specified, the supplier may utilize his own facilities or any commercial laboratory acceptable to the Government. The Government reserves the right to perform any of the inspections set forth in the specification where such inspections are deemed necessary to assure supplies and services conform to prescribed requirements.

TABLE III MECHANICAL PROPERTIES

Material	Section Size		Minimum Tensile Strength ksi	Minimum Yield Strength at 0.2% Offset ksi	Minimum Elong. %	Minimum R. A. %
	Hot-Worked	Heat-Treated				
Type I	5" and less	2-1/2" and less	145	130	8	20
Type II	5" and less	5" and less	140	125	10	20

4.2 Classification of Tests. All the tests specified herein for the examination and testing of alloyed titanium are classified as quality conformance tests.

4.3 Lot. A lot shall consist of forgings and forging stock of the same heat and the same thickness produced at the same time and submitted for inspection at one time.

4.4 Examinations

4.4.1 Examination of Product. Sufficient spot checks shall be made to insure compliance with this specification with respect to identification, tolerance, and workmanship requirements.

4.4.2 Examination for Preparation for Delivery. Preparation for delivery shall be examined for conformance to section 5.

4.5 Chemical Analysis

4.5.1 Sampling. At least one sample for chemical analysis shall be taken from materials of each heat. Each sample shall consist of sufficient material to provide not less than 2 ounces of chips. Each sample taken shall be analyzed separately, and if any sample fails to meet the chemical requirements, the heat represented shall be rejected.

4.5.2 Method. Analysis shall be by wet chemical, spectrochemical, vacuum-fusion methods, or other methods acceptable to the Government, as appropriate.

4.6 Tensile Test

4.6.1 Sampling. Two or more samples shall be selected to represent each lot of material. Not more than one test sample shall be taken from any one piece in the lot.

4.6.2 Preparation of Specimens. Tensile test specimens shall conform to types R1, R2, R3 and R5 of method 211 of Fed. Test Method Std. No. 151. Where dimensions permit specimens shall be machined from such position that the direction of loading shall be transverse to the direction of major working (grain flow). Tensile test specimens shall be located at the center of the section on items up to and including thickness or diameter of 1-1/2 inches and at the half radius position on larger sections.

4.6.3 Method. Tensile tests shall be conducted in accordance with method 211 of Fed. Test Method Std. No. 151.

4.7 Rejection. Where failure of a sample or specimen is ascribed to faulty material, the entire lot shall be rejected.

5. PREPARATION FOR DELIVERY

5.1 Packaging and Packing. Materials shall be prepared for shipment in accordance with the requirements of MIL-STD-163 applicable to the packaging and packing of cold-finished alloy steel bars, except that preservative coating is not required, and identification marking shall be as specified herein.

5.2 Marking of Shipments. Interior packages and exterior shipping containers shall be marked in accordance with MIL-STD-129. The identification shall include the following information listed in the order shown.

Stock No. or other identification number as specified in the purchase document*
TITANIUM-ALLOY FORGINGS, AND FORGING STOCK (as applicable)
Shape**, Heat No. **, Length**, Width**, Thickness**, Type**, Composition**
Specification
Manufacturer's name or trade-mark**

*Note: The contractor shall enter the Federal Stock No. specified in the purchase document or as furnished by the procuring activity. When the Federal Stock No. is not provided or available from the procuring activity, leave space therefor and enter Stock No. or other Identification when provided by the procuring activity.

**Applicable data to be entered by the manufacturer.

6. NOTES

6.1 Ordering Data. Procurement documents should specify the following:

(a) Title, number, and date of this specification.
(b) Commercial designation.
(c) Type and composition required (see 1.2).
(d) Dimensions, shape, and tolerances (see 3.4 and 3.4.1).
(e) Exact lengths and length tolerances if mill lengths are not acceptable.
(f) Mechanical properties of sections larger than covered by this specification.
(g) Level of packaging and packing desired (see 5.1).

REFERENCES

1. R.F. Simenz, W.L. Macoritto, "Evaluation of Large Titanium Alloy Forgings", AFML-TR-65-206, Lockheed-California Company, July 1965.

2. James E. Coyne, "The Evaluation of IMI 679 Titanium Alloy As A Compressor Disc Material" RD 64-137, MD&E #19, Wyman-Gordon Company, August 31, 1964.

3. "Ti-679 High Temperature Titanium Alloy for Short-Time Strength, Creep and Stability", Titanium Metals Corporation of America, November, 1964.

4. "Current Methods of Fracture-Toughness Testing of High Strength Alloys with Emphasis on Plane Strain", DMIC Report No. 207, August 31, 1965.

5. "Metallurgical and Mechanical Properties of Titanium Alloy Ti-679", Titanium Metals Corporation of America, August, 1965.

6. "A New Stress Corrosion Cracking Test Procedure for High Strength Alloys", B. F. Brown, Head of Physical Metallurgy Branch Metallurgy Division, U.S. Naval Research Laboratory, ASTM Preprint, May, 1965.

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13. ABSTRACT

This report describes the evaluation of large, closed-die forgings of two titanium alloys. Four forgings each of Ti-6Al-4V and IMI 679 were used in the evaluation. Property tests that were conducted included tension, notched tension, compression. Tuckerman modulus, shear, bearing, fracture toughness and smooth and notched axial fatigue. Thermal exposure and susceptibility to delayed failure in salt water were also evaluated in each alloy. Static properties were generally slightly better in the Ti-6Al-4V alloy. However, the IMI 679 provided significantly better smooth and notched fatigue values. Both alloys had good fracture toughness at room temperature and at -110°F. Static and fatigue tests were conducted on one forging each of Ti-6Al-4V and IMI 679. The Ti-6Al-4V part gave the better static test performance. Both titanium alloys exhibited strength/weight efficiency superior to a 4340 steel part tested in a previous program. The fatigue test life of the IMI 679 part was approximately 60% better than that of the Ti-6Al-4V part; however the Ti-6Al-4V may not have been a representative sample due to minor metallic inclusions found in the fatigue tested parts. Based on these results the IMI 679 alloy appears to show promise for improved performance over Ti-6Al-4V as well as over other titanium alloys in fatigue critical applications. The material property data and forging static and fatigue test results indicate that Ti-6Al-4V and IMI 679 compare favorably with two other titanium alloys, Ti-6Al-6V-2Sn and Ti-13V-11Cr-3Al, which were evaluated in a previous program.

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